Teachers as Curriculum Designers:
Understanding STEM Pedagogical Design Capacity

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Dedication

This thesis is dedicated to my family. You are the most important thing I have.

Abstract

Background/Context: Science is in the midst of reform, shifting away from teaching science and mathematics in isolation from one another, toward a model that prioritizes integration of science, technology, engineering, and mathematics (STEM) learning environments. Since teachers are the most important factor in determining the success and sustainability of reform ideals (Luft & Hewson, 2014), understanding how to effectively support the professional learning of teachers to plan, teach and assess integrated STEM curriculum is essential to STEM reform.

Purpose/Focus of Study: This dissertation presents a model for understanding how to support and facilitate collaborative teacher design teams engaged in STEM curriculum development. The study focuses on co-development, collaboration, and refinement of integrated STEM curriculum units, and the social construction of knowledge as the teacher design team examines student work and redesigns curriculum. The study is framed around the theoretical construct of the reciprocal relationship between teachers and curriculum -- how teachers' design and use of curriculum is influenced by the curricular resource itself. At the same time, the materials "change, move, perturb, and inform" (Bruner, 1977, p. xv) to advance teachers' knowledge through use. Underlying curriculum use, is a set of resource tools, some physical and others intellectual, that teachers bring to designing instruction that affects decisions about how to interact with curriculum: to use with relative fidelity (offload), to make changes that preserve the core ideas in the curriculum (adapt), or make significant changes that reflect the teacher's knowledge and skills (improvise). Decisions to offload, adapt or improvise curriculum

materials can be understood by close analysis of interactions between the resources that informed the decisions.

Intervention: The analysis of teacher professional learning is typically approached by measuring outcomes such as teacher or student learning (Brown, 2002). However, pedagogical design capacity (PDC) suggests an alternative method for understanding teacher professional growth as a process. The method consists of (i) identifying aspects that characterize curricular resources (procedures, domain representation, physical object); (ii) identifying aspects that characterize teacher resources (subject matter knowledge, pedagogical content knowledge, teacher goals and beliefs); and (iii) investigating how the former and the latter interact to inform decisions to offload, adapt or improvise with curriculum materials. In addition, evaluation of professional learning is often approached with the focus on individual teachers. However, the teachers in this study worked in teacher design teams. Therefore, the collaborative approach necessitated a model that honored and supported the knowledge, goals and experiences of the group. To support collaborative work, and to examine the effects of collaborative redesign of the STEM curriculum, two protocol interventions were developed. These facilitated the teams' post-implementation examination of student work (*Looking at Student Work* protocol) and redesign of curriculum (*Thinking Through a Task* protocol).

Research Design Approach: A multiple-case study research design was used to take advantage of analytic benefits that support viability of outcomes for theoretical generalization (Yin, 2014). Three teacher design teams were selected from multiple schools across a large urban district. The three cases were *contrasting* in nature (Yin, 2014), in that they allowed for investigation of variability across elementary and middle school contexts, across 3rd-6th grades, and across Earth Science and Physical Science. The design choice of contrasting cases was made to illustrate similar and different strategies for PDC development. The analytic approach consisted of individual case analysis, followed by cross-case synthesis to build upon the knowledge generated from analysis of individual cases. Cross-case synthesis is an analysis strategy that embodies making a "new whole out of the parts," with the goal of making unique connections and interpretations that could not be made from individual case analysis (Cruzes, Dybå, Runeson, & Höst, 2015, introduction para. 5, 2015).

Conclusions/Recommendations: This study found that collaborative resources were important tools the teams drew upon to hone and clarify their ideas about STEM curriculum. Two of the collaborative resources were not surprising: (i) protocol and facilitation strategies; (ii) co-design and evaluation of assessment tools. However, storytelling was an unanticipated finding. The teams used individual storytelling to share classroom events, they used co-storytelling to co-construction meaning, and parallel storytelling to introduce previous related experiences. Storytelling served as a resource to grow their STEM PDC. This study's findings led to an adaptation of the Design Capacity Enactment Framework (Brown, 2002) that includes a new category of resources -- Collaborative Resources. This new model suggests that professional development for STEM reform can be enhanced by deliberate consideration of collaborative resources, in addition to curricular and teacher resources.

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Chapter 1: Introduction

"It is virtually impossible to create and sustain over time conditions for productive learning for students when they do not exist for teachers" (Sarason, 1990, p. 45).

Organization of the Dissertation

Chapter 1 provides a rationale for the study, the purpose and its potential significance, and concludes with definitions of important terms. Chapter 2 provides a description of the theoretical and conceptual backgrounds for the study, and a review of the relevant literature. Chapter 3 summarizes the research methods used to carry out the study. The chapter describes the participants, the data collection, and analysis methods used. Chapter 4 presents the analysis of the individual cases in this study. The chapter is organized around several assertions, each supported with illustrative critical incidents. Chapter 5 presents a cross-case synthesis of the three individual cases. The chapter builds upon the body of knowledge generated from analysis of individual cases to compare case outcomes and patterns across cases. The chapter is organized around three meta-assertions, each with corresponding synthesis of the major patterns and themes generated from the individual case analysis. Chapter 6 presents conclusions and theoretical generalizations of the findings, implications, and suggestions for further research.

Rationale

In recent years, integrated approaches to teaching and learning of science, technology, engineering and mathematics (STEM) have received increased attention as the call to improve the quality of science curriculum and instruction have gained momentum. Integrated STEM learning environments refer to integration of STEM disciplines rather than separating the disciplines with artificial divides that do not reflect the way people use knowledge in the real world (Moore & Glancy, 2013). The National Academy of Engineering (NAE) and the National Research Council (NRC) have advocated for increased attention to integrated STEM has been advocated for many reasons including ensuring science is accessible and relevant for all students (NAE & NRC, 2014), maintaining America's global competitiveness (Moore, Stohlmann, Wang, Tank & Roehrig, 2014), and, in part, to greater understanding of how students best learn science (DeBoer, 2014). In this regard, STEM education is in the midst of reform that shifts away from teaching STEM subjects in isolation from one another toward a model that prioritizes integrated STEM learning environments, instructional methods and authentic learning tasks that apply engineering contexts.

Implementation of integrated STEM reform vision necessitates STEM-specific professional development (PD) and curriculum development. While reform policy statements provide a common vocabulary for reform, and a useful tool for understanding salient features of STEM integration, they do not articulate guidelines for how to proceed. This dissertation addresses these interrelated issues.

Teacher Professional Development

In 1996, a report of the National Commission on Teaching and America's Future (NCTAF), *What Matters Most: Teaching for America's Future*, outlined recommendations for education reform and pointed to the need to reinvent teacher PD. The report acknowledged that the most successful PD is embedded in teacher practice, ongoing, and encourages communities of professional practice. The report brought attention to both existing models of science teaching and learning and new PD models that embraced the report's recommendations for more closely linking expectations for student learning to teacher learning.

Professional development can be defined as "the ongoing learning experience of a teacher" (Luft & Hewson, 2016, p. 889). The purpose of PD is to support teachers in enhancing, refining and reconstructing their practice (Luft & Hewson, 2016). There are different models of professional development programs (PDP), each with underlying assumptions about how people learn and develop new understandings. Early definitions of professional learning often took a recipient approach, where the teacher's role was to receive new knowledge and implement it (Le Fevre, Timperley & Ell, 2016). Gradually definitions changed, reflecting a more complex picture where learning was "both personal and professional, individual and collective, inquiry based and technical (Lieberman, 1995, p. 592). In recent years, greater attention has been given to embedding PD in teacher practice, and structuring it within communities of professional practice to take advantage of the role social and cultural aspects of learning play in influencing teacher learning and development (Borko, 2004; Putnam & Borko, 2000).

Conceptions of Professional Development

Communities of practice (CoP) is a term originally used by Jean Lave and Etienne Wenger (1991) in their seminal work *Situated Learning: Legitimate Peripheral Participation* to describe how knowledge is embedded in practice. A CoP is defined by three features: a community, a shared identity, and a shared practice to learn by all participants (Wenger, 1998). Central to CoPs is *legitimate peripheral participation*, a process of social learning that occurs when people with differing levels of knowledge collaborate around a common topic of interest. A situated perspective views learning not a property of individuals (the cognitive view), but as a relational property of individuals in context and in interaction with one another (the situated view) through legitimate peripheral participation in CoPs (Hoadley, 2012). CoPs encourage and invite collaborative learning by distributing cognitive resources across groups of people (Putnam & Borko, 2000; Borko, 2004). By engaging in legitimate peripheral participation, newcomers become experienced members of the community and, eventually, old timers, while more experienced members of the community grow their knowledge further (Lave & Wenger, 1991). Professional development programs (PDP) that utilize CoPs are premised on the belief that, teachers learn science best by investigating for themselves to build their own understanding, as opposed to being told about what is already known (Loucks-Horsley, Stiles, Mundry, Love & Hewson, 2010). Such a perspective is premised on a Sociocultural Theory.

A sociocultural theory of teacher professional development approaches learning from the perspective that knowledge is constructed through cultural mediation and social interactions that take place with legitimate peripheral participation in CoPs. A sociocultural view of curriculum use and development suggests there is an "inter-relationship" between individuals, their context, and the resources available to them (Wyse, Hayward & Pandya, 2016, p. 8). Furthermore, the inter-relationships can be a source of empowerment (Wyse, Hayward & Pandya, 2016). A sociocultural stance views the role of the teacher as multifaceted, having multiple roles regarding curriculum. Teachers' everyday practice includes that of enactors of curriculum, creators of curriculum, and active engagement in education policy through curriculum development that meets the needs of their students (La Fevre, Timperley & Ell, 2016).

Putnam and Borko (2000) infuse sociocultural notions of learning into PD program development, arguing that situating learning in CoPs, promotes social interactions that develop a shared repertoire of knowledge and experiences, (Akerson, Cullen & Hanson, 2009). This approach to PD moves away from a model that relies on experts conveying information and learners acting as passive recipients, toward a learner-centered model that honors experiences of participants (La Favre, Timperley & Ell, 2016). Whereas traditionally PD has emphasized new skills and knowledge without helping teachers examine, rethink and transform their thinking and beliefs (Louck-Horsely, et al., 2010), learner-centered models recognize teachers benefit from opportunities to evaluate and reflect upon their work (Borko, 2004). Key elements that align with a sociocultural perspective on PD include (Borko, 2004, p. 6):

- The professional development program;
- The teachers, who are the learners in the system;
- The facilitator, who guides teachers as they construct new knowledge and practices; and
- The context in which the professional development occurs.

Having these four elements embedded in PD does not ensure success. Rather, the strategic alignment of the PD program and context, combined with teachers engaged in active learning facilitated by a process to support teachers supports the vision of science reform and the reinvention of teacher PD. Teachers need opportunities to evaluate and reflect upon their work within communities of professional practice (Borko, 2004). Such a conception of reform-based PD is about "constructing knowledge, not receiving it; understanding and applying, not recall; thinking and analyzing, not accumulating and memorizing; and being active, not passive" (Mohler, Yun, Carter & Kasak, 2009, p. 20, quoting Marlowe & Page, 2005). Conceptions of professional learning where PD activities are extended over time and encourage the development of teachers' learning communities also has implications for the role curriculum material play since it is impossible to conceive of reform-based PD that can transform teacher practice without curriculum materials.

One way to accomplish a learner-centered model is to ground professional learning on evidence of student and teacher learning (Le Fevre, Timperley & Ell, 2016). Using protocols to facilitate collaborative conversations is one way to accomplish a model of professional learning that supports learner-centered strategies and takes advantage of the social nature of learning. A protocol is a set of step-by-step guidelines used to structure professional conversations ensuring that meeting, planning, or group-collaboration time is used efficiently, purposefully, and productively (Glossary of Education Reform). Such an approach places the learner in the position of providing and receiving feedback, which is crucial for self-regulated learning to occur (McDonald, Mohr, Dichter & McDonald, 2013). The idea behind sociocultural theory [and protocols] is that people influence each other's cognition: "Both individual and collective knowledge construction occurs through processes of interaction, negotiation and cognition" (Le Fevre, Timperley & Ell, 2016, p. 317). Protocols facilitate the process by providing enough structure to keep the conversation focused on salient topics of interest, but open-ended enough to invite participant ideas, feedback and personal associations (McDonald et al., 2013).

Curriculum has become a vital part of education reform because it is the primary tool teachers rely on in their daily professional lives (Ben-Peretz, 1990) to inform the content to be taught, pedagogy and assessment practices (Wyse, Hayward & Pandya, 2016). Due to the integral nature of curriculum to teachers' daily work and to reform ideals, PD that engages teachers in design and development of curriculum materials, and holds promise for teacher learning and for sustaining reform goals.

Teachers and Curriculum

The question of how to effectively support teacher professional learning and development has been "seen as a curriculum problem (1920s-1950s) to a training problem (1960s-1980s), to a learning problem (1980s-2000s) to a policy problem (1990 to present)" (Wallace & Loughran, 2012, p. 295). Partly because of changing values in society, and partly due to the fact that we know more about how people learn (DeBoer, 2014), there has been a growing interest in the intersection of student learning and teacher learning (Wallace & Loughran, 2012), where curriculum is conceived of as more than a plan for learning (Taba & Spalding, 1962) and as a tool for teacher learning (Davis & Krajcik, 2005). Reconceiving curriculum use and development as a resource for teacher learning suggests curriculum can play an important role in PD that supports reform goals (Huizinga, Handelzalts, Nieven & Voogt, 2014).

Conceptions of Curriculum Use and Development

Curriculum materials in a variety of forms including textbooks, lesson plans, and externally designed curriculum units composed of multiple closely aligned lesson plans (Ben-Peretz, 1990). Curriculum can also be conceived of more expansively, as a course of study that includes the what students study and what teachers teach, and educational experience itself (Jung & Pinar, 2016). For the purpose of this study, curriculum will be defined as having four basic elements: establishing learning objectives, selection of learning activities, organization of learning activities, and assessment of learning.

The purpose of curriculum has been conceived of as a plan for learning (Taba & Spalding, 1962). Bruner (1977) conceived of curriculum as a tool as much for teachers as for students, because teachers interpret curriculum to meet the needs of their particular students. More recently, the notion that curriculum serves as a tool for teachers has been elaborated upon, conceived of as "educative" for teachers" (Ball & Cohen, 1996; Davis & Krajcik, 2005). Conceiving of curriculum as having educative value for teachers who use it, shifts the role of curriculum from being solely a tool for guiding classroom instruction toward a strategy for teacher learning and supporting educational reforms (Huizinga et al., 2014).

Teachers as designers of curriculum. Given the potential curriculum holds as an educative tool and for supporting PD goals, engaging teachers in STEM curriculum design holds promise for enhancing teacher learning and success of reform goals. Teachers regularly act as curriculum designers in their regular practice as they interpret and modify curriculum materials for classroom use (Brown, 2002, 2009; Brown & Edelson, 2003). As a result, bringing "practical knowledge" of students, classrooms and teaching experience to reform efforts (van Driel, Beijaard & Verloop, 2001, p. 137). Participation in teacher design teams that focused on curriculum design found important benefits for teacher professional growth that included improved self-confidence and pedagogical content knowledge (PCK) development (Voogt, Westbroek, Handelzalts, Walraven, McKenney, Pieters & de Vries, 2011).

In this chapter I have outlined several facets of teacher professional learning and development including: 1) STEM science reform; 2) the importance PD; 3) the potential of engaging teachers as curriculum designers as a tool for professional learning and sustaining reform; and 4) the benefits of using protocols to support collaborative learning. In the following I will elaborate on the topic, articulating the purpose and significance of this study as they relate to integrated STEM curriculum.

Purpose of Study and Potential Significance

The purpose of this study is to understand STEM PDC -- a teacher's ability to draw upon personal and curricular resources to craft productive instruction (Brown, 2002, 2009; Brown & Edelson, 2003; Beyer & Davis, 2013) -- and the role protocol interventions play in affording and constraining PDC development. Just as cultural mediation and social interactions support learning and development, curriculum serves as a tool that can afford or constrain learning. Curricular tools mediate teacher learning in the sense that they help teachers accomplish tasks they could not accomplish on their own (Brown, 2009). Framing teaching as a design activity brings teacher practice and reform goals in closer alignment, and has the potential to inform how to best implement and develop PDPs to support integrated STEM reform efforts. Furthermore, the ability to enact or design curriculum cannot be fully understood in terms of individual instructional outcomes for teacher and student learning (Brown, 2002, 2009). Rather, understanding how social interactions and cultural tools (curriculum) mediate teacher learning and development hold promise for success and sustainability of integrated STEM learning environments. Therefore, it is worthwhile to extend the PDC framework to STEM curriculum, and to build upon our current understanding of how PDC develops by investigating PDC within collaborative teacher design teams, and how protocols afford and constrain the process.

Gaps in the Literature

Research that focuses on the dimensions of integrated STEM education (goals, outcomes, implementation, nature and scope of integration, etc.) is necessary but insufficient for characterizing successful STEM curriculum design and use. Research that simply examines dimensions of individual teacher's learning and development without attention to the collaborative process in which it took place, neglects the socially constructed nature of learning. Missing from the STEM literature is a characterization of how capacity for understanding STEM curriculum develops, and how to effectively design PD. Evaluation of PD strategies typically focuses on the individual teacher (Putnam & Borko, 2000); Yet, we know from the literature on professional learning that teacher learning is maximized when it is "(a) situated in particular physical and social context; (b) social in nature, and (c) distributed across the individual, other persons and tools" (Putnam & Borko, 2000, p. 4). This study can contribute to an understanding of approaches to effective PD by extending what is known about STEM PDC development within professional communities of practice. Research on PDC has, to this point, only been studied in relation to pre-written, single subject curriculum and with individuals.

This study explores PDC development of TDTs using teacher-designed curriculum. The unit of study is the group. In addition, this study is applied to integrated STEM curriculum, and can provide insight into the process of STEM PDC development. Finally, using protocol interventions to structure the collaborative conversations has the potential to inform how the use of protocols to guide professional learning conversations affords and constrain STEM PDC development.

Research Questions

Three research questions guide this study, the first addressing PDC and the supporting questions to understand the role protocol interventions play in the process:

1. How does STEM PDC develop in teacher design teams while examining student work and redesigning a co-developed curriculum?
2. How does the use of a protocol for examining student work afford and constrain collaboration and redesign of co-developed curriculum?
3. How does the use of a protocol for designing curriculum materials afford and constrain collaboration and redesign of co-developed curriculum?

Potential Significance of the Study

Since “it is virtually impossible to create and sustain over time conditions for productive learning for students when they do not exist for teachers” (Sarason, 1990, p. 45), a complete understanding of how STEM PDC develops is necessary. This means understanding both the outcomes (student and teacher learning) and the process processes (PDC development) by which understanding of STEM reform develops. Without a complete understanding of what STEM curriculum is, and how to effectively structure PD to support teacher professional learning related to STEM curriculum and instruction, implementing and sustaining STEM reform will be difficult. Collaborative STEM curriculum design offers a way of actively engaging teachers in STEM reform by tapping into their professional knowledge of the classroom, and supporting their learning specific to integrated strategies and approaches to the STEM disciplines. However, the shortage of studies that emphasize the process of how understanding of STEM curriculum develops, and the absence of studies that focus on how STEM PDC and the role protocols play in the process, positions this study to make a significant contribution to the STEM reform literature. This study provides significant knowledge related to PDC, a construct which has not been applied to integrated STEM. Finally, this research study takes the group as the unit of analysis, whereas PDC has currently only been used with individual teachers. This study can provide significant insights into the development of PDC as a collaborative process and how protocols support and constrain STEM PDC development.

Definitions

Curriculum design and *curriculum development* in this study refers to two closely related terms to describe how teachers work in conceptualizing and using curriculum materials. Curriculum design includes five types of design activity: interpretation, selection, reconciliation, accommodation and modification (Brown, 2002, 2009). Curriculum development is a more encompassing term, including analysis, design, development, implementation and evaluation (Huizinga, Handelzalts, Nieveen & Voogt, 2014).

Curricular and Personal Resources in this study refers to the considerations teachers attend to as they engage in curriculum development and redesign (Beyer & Davis, 2012).

Curricular resources refer to the material resources in the co-developed curriculum the TDTs created. Personal resources refer to “intellectual” resources teachers bring to curriculum design developed through (Brown, 2002, 2009) an “array of experiences, dispositions, beliefs, knowledge and abilities” (Beyer & Davis, 2012, p. 388) the TDTs bring to the practice of curriculum development.

Design Capacity Enactment Framework (DCE) in this study refers to an analytic framework for describing how resources interact to result in decisions to craft instruction.

Pedagogical Design Capacity (PDC) in this study refers to a type of personal resource that encompasses a teacher’s ability to identify and mobilize both personal and curricular resources to craft instruction (Brown, 2002; Brown & Edelson, 2003).

Teacher Design Teams in this study represents a community of practice (Lave & Wenger, 1991; Wenger, 1998) focused on pursuing their interest in understanding STEM curriculum.

Chapter 2 : Literature Review

"We shape our tools and thereafter our tools shape us." *Marshall McLuhan*

This chapter reviews the literature on topics relevant to the nature of teacher-curriculum relationship (Ben-Peretz, 1991), and development of teachers' understanding of STEM curriculum. There are three closely related bodies of literature relevant for conceptually framing the study: STEM reform and curriculum, the teacher-curriculum relationship, and the construct of Pedagogical Design Capacity and its relationship to the Design Capacity Enactment analytic framework. In addition, the Sociocultural Theory literature theoretically frames this study. In the first section, I present the literature related to STEM curriculum and professional development. In the second section, I present the literature on engaging teachers as curriculum designers for reform-based professional development. In the third section, I present pedagogical design capacity (PDC), and the Design Capacity Enactment (DCE) framework, and their relationship to understanding teacher professional learning and development. The final section describes Sociocultural Theory, and its relationship to PDC development. I also describe the relationship between sociocultural theory and the use of protocols to support teacher learning and reform goals.

Background on Education Reform

With the publication of *A Nation at Risk* (National Commission on Excellence in Education (NCEE), 1983), an era of concern about the quality of American education was ushered in. The 1980s and 1990s saw the confluence of several events that drove the course of education policy in ways that still influence education policy today: standards-based education reform, awareness of the need to reinvent teacher PD in ways that include teachers as partners in reform, and the publication of two foundational documents specific to science: *Science for All Americans* (Rutherford & Ahlgren, 1989) and the *Benchmarks for Science Literacy* (American Association for the Advancement of Science, 1993). These events instigated new research on curriculum development (Wyse, Hayward & Pandya, 2016, paraphrasing Connelly & Clandinin, 1988), the relationship between teachers and curriculum (Remillard (1999), and the processes by which teachers interpret and use curriculum materials (Ben-Peretz, 1990).

In 1990 the National Education Goals Panel was established and new recommendations for content standards were articulated in five core subject areas. The purpose of the standards was to specify what students should know and be able to do in the classroom and establish goals for teaching (DeBoer, 2014). The 1996 *What Matters Most: Teaching for America's Future* report pointed to the need to support standards-based reform efforts and reinvent teacher professional development. The report recognized the dual role teachers play for student outcomes and success of reform efforts. The report's recommendations were premised on three ideas (p. 10):

1. What teachers know and can do is the most important influence on what students learn.
2. Recruiting, preparing, and retaining good teachers is the central strategy for improving our schools.
3. School reform cannot succeed unless it focuses on creating the conditions in which teachers can teach, and teach well.

Prior to these events, teachers were not typically actively involved in reform efforts. Rather, the role of teachers was largely relegated to users of teacher-proof curricula (Ben-Peretz, 1991). The closer connections between teacher practice and education reform inspired researchers began to focus on the relationship between teachers and curriculum, and it became a priority to understand what a teacher brings to curriculum design and how modifications to curricular materials played out in the classroom (McFadden, 2015).

STEM Reform

Recognizing the need for fundamental change in K-12 science education, the National Research Council (NRC) and National Association of Engineers (NAE) sponsored a committee to formulate a vision for science education reform. The vision for reform is informed by the Next Generation Science Standards (NGSS), and outlined in the *Descriptive Framework* (Honey, Pearson & Schweingruber, 2014). NGSS is a set of K-12 science education standards developed by the NRC in collaboration with a consortium of 26 states. The Standards marry content and disciplinary practices, emphasize depth over breadth, and introduce engineering and technology into standards that had previously only included science and mathematics (NGSS, 2013). The term STEM has been used to describe integrated approaches to science, technology, engineering and mathematics reform.

The *Descriptive Framework* outlines: the nature and scope STEM integration efforts should take, focus areas for implementation of STEM initiatives, and goals and outcomes for teachers and students. Figure 2.1 provides an overview of the *Descriptive Framework* and the established priorities for integrated STEM learning environments.

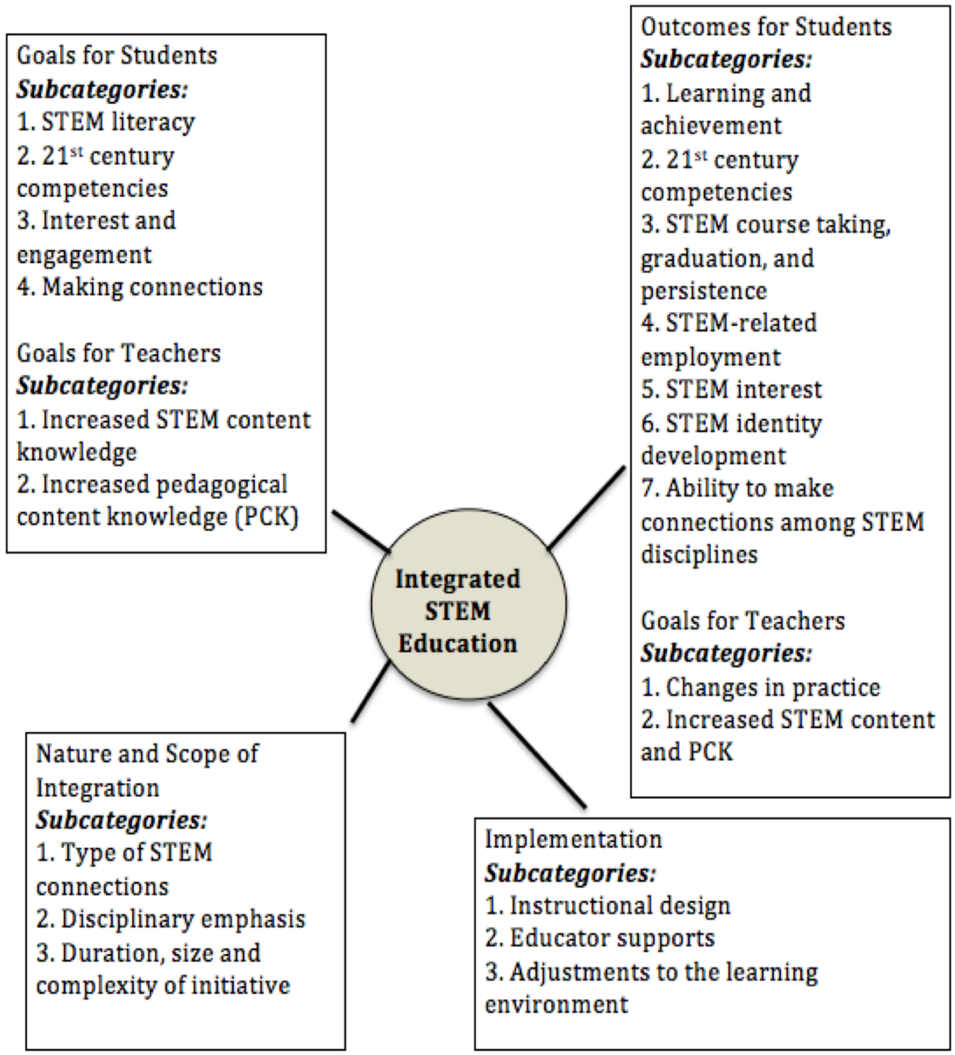


Figure 2.1. This figure is the *Descriptive Framework* (NRC, 2014) outlining priorities for integrated STEM curriculum.

The *Descriptive Framework* is intended to establish priorities for teachers and students, and provide a common vocabulary from which to create and research STEM initiatives for K-12 education (Honey, Pearson & Schweingruber, 2014). It also describes a broad range of educational experiences related to integrated STEM reform.

Conceptions of STEM curriculum. There are several conceptions of what STEM curriculum is, including (Bybee, 2010): (i) a term for science and mathematics being taught in an integrated fashion; (ii) a term for increased emphasis on technology and engineering in the K-12 curriculum; (iii) a term that stresses development of 21st Century skills; (iv) a term that stresses an integrated curricular approach to addressing global issues. In this study, STEM aligns with an integrated curricular approach.

An integrated approach to STEM organizes instructional materials around cross-disciplinary issues, applying multiple STEM disciplines to address human problems or needs shifting the "focus from simply identifying issues common to the disciplines and then tackling them separately, toward addressing those issues through meaningful integration of the subjects (Moore & Glancy, 2013, p. 3). In the case of this research study, the distinguishing feature of STEM is *integration*. *Integration* refers to integrating multiple STEM subjects in a manner that makes meaningful connections between the subjects and real-world problems (Moore & Glancy, 2013; Moore, et al., 2014), often using mathematics, science or technology to engage in an engineering design task (Moore & Glancy, 2013).

The rationale behind the integration of the STEM disciplines through engineering is that engineering can provide a "natural connector" for integration either through content or the context of the learning (Moore et al., 2014, p. 6). Engineering by its nature, uses mathematical and scientific ideas to solve problems, which promote learning scientific or mathematical concepts. Engineering can also provide authentic and motivating context if the learning activities are framed around socially relevant issues, for example focusing the unit on a company that is the student's client or a real-world issue such as bioengineering (Moore et al., 2014). Finally, engineering design experiences are ill-structured problems that can be approached in a variety of ways and do not have one solution (Householder & Hailey, 2012). Open-ended problems require complex thinking but also allow for individual differences in students and promote teamwork, which may improve student motivation, interest and collaboration (Householder & Hailey, 2012).

Integrated STEM curriculum. A two-year study by the Committee on K-12 Engineering Education of the NAE resulted in a report that described the scope and nature of engineering. The report recommended that K-12 engineering should: emphasize engineering design, incorporate developmentally appropriate science, mathematics and technology, and emphasize engineering "habits of mind" (systems thinking, creativity, optimism, collaboration, communication and ethical considerations) (Householder & Hailey, 2012, p. 43). These recommendations inspired development a framework for assessing K-12 engineering curricula utilized by the teachers in this study. The framework is organized around key indicators with corresponding sub-categories. Figure 2.2 shows the *Framework for Quality K-12 Engineering Education* and associated key indicators and sub-categories, each with a corresponding description.

Key Indicator		Description
Complete Processes of Design (POD)		Design processes are at the center of engineering practice. Solving engineering problems is an iterative process involving preparing, planning and evaluating the solution. Students should understand design by participating in each of the sub-indicators (POD-PB, POD-PI, POD-TE) below.
Sub-indicators of POD	**Problem and Background (POD – PB)**	Identification or formulation of engineering problems and research and learning activities necessary to gain background knowledge.
	Plan and Implement (POD – PI)	Brainstorming, developing multiple solutions, judging the relative importance of constraints and the creation of a prototype, model or other product.
	Test and Evaluate (POD – TE)	Generating testable hypotheses and designing experiments to gather data that should be used to evaluate the prototype or solution, and to use this feedback in redesign.
Apply Science, Engineering, Mathematics Knowledge (SEM)		The practice of engineering requires the application of science, mathematics, and engineering knowledge and engineering education at the K-12 level should emphasize this interdisciplinary nature.
Engineering Thinking (EThink)		Students should be independent and reflective thinkers capable of seeking out new knowledge and learning from failure when problems arise.
Conceptions of Engineers and Engineering (CEE)		K-12 students not only need to participate in an engineering process, but understand what an engineer does.
Engineering Tools, Techniques, and Processes (ETool)		Students studying engineering need to become familiar and proficient in the processes, techniques, skills, and tools engineers use in their work.
Issues, Solutions, and Impacts (ISI)		To solve complex and multidisciplinary problems, students need to be able to understand the impact of their solutions on current issues and vice versa.
Ethics (Ethics)		Students should consider ethical situations inherent in the practice of engineering.
Teamwork (Team)		In K-12 engineering education, it is important to develop students' abilities to participate as a contributing team member.
Communication Related to Engineering (Comm-Engr)		Communication is the ability of a student to effectively take in information and to relay understandings to others in an engineering context.

Figure 2.2. This figure shows the *Framework for Quality K-12 Engineering Education* (Moore et al., 2014) including key indicators, subcategories and descriptions of each.

The *Framework for Quality K-12 Engineering Education* characterizes an integrated approach to STEM curriculum as requiring an engineering context, the process of design (POD), integration of science, engineering and mathematics (SEM), engineering and engineering habits of mind, solutions, ethics, teamwork, and communication (Moore et al., 2014). In addition to providing a tool for evaluating STEM curriculum, the framework provides a common vocabulary for what constitutes quality K-12 engineering education.

This study was affiliated with a larger professional development program (PDP), *EngrTEAMS: Engineering to Transform the Education of Analysis, Measurement, and Science in a Team-Based Targeted Mathematics-Science Partnership.* The goals of the professional development were to produce standards-based STEM curriculum units for grades 4-8 that taught science and mathematical concepts related to data analysis and measurement, using an engineering design-based approach. The *Framework for Quality K-12 Engineering Education* were developed by the *EngrTEAMS* planning team and utilized during the PD with teachers. I discuss *EngrTEAMS* in greater detail in chapter 3.

Professional Development and STEM Reform

Professional development for teachers is a component of virtually every effort for improving education (Guskey, 2002). Professional development programs vary, but all share the ultimate goal of improved student outcomes (learning, experiences, engagement, etc.) and teacher learning and development (knowledge, teacher practice, attitudes and beliefs, etc.). Ineffective professional development programs share two factors, lack of consideration for: "what motivates teachers to engage in professional development; and the process by which change in teachers typically occurs" (Guskey, 2002, p. 382). Research suggests teachers want to participate in PD that expands their knowledge and skills, but they also want the PD to be practical and relevant to their day-to-day practice and student needs (Guskey, 2002).

Science teacher professional development. The 1996 recommendations for PD were premised on the ideas that what teachers know and can do is the most important influence on what students learn, that recruiting, preparing, and retaining good teachers is the central strategy for improving our schools, and recognized that school reform cannot succeed unless it focuses on creating the conditions in which teachers can teach, and teach well. The recommendations along with a substantial amount of research into effective PD practices has generated a wide variety of strategies and approaches to effective teacher PD programs. While there is not one single strategy or approach, it is widely viewed that PD should be focused on substantive issues of practice, embedded in teacher practice, ongoing, and organized around participation in communities of professional practice (Loucks-Horsely, et al., 2010).

Reinventing science teacher professional development. It is widely accepted that professional development goals for teachers include new knowledge and skills to change practice, attitudes and beliefs. Usually PD emphasizes change through new instructional approaches, new curriculum materials, or changes in classroom procedures (Gusey, 2002). However, there is evidence that changes in practice, attitudes and beliefs that persists long term only takes place after teachers see evidence of improved student outcomes (Guskey, 2002). This suggests that change is derived from classroom practices (Guskey, 2002), and that effective PD must consider more than the content of the PD to include attention to *how* it is delivered.

Arenas of effective professional development. Guskey (1986, 2002) present a Model of Teacher Change that is organized around three arenas of effective PD practices developers must consider (Guskey, 2002, p. 386-388):

- *Recognize that Change is a Gradual and Difficult Process for Teachers*;
- *Ensure that Teachers Receive Regular Feedback on Student Learning Progress*;
- *Provide Continued Follow-Up, Support and Pressure*;

These three arenas of the Model of Teacher Change have implications for PD planning, implementation and follow-up. First, change takes time, will not take place uniformly, and brings uncertainty that often causes anxiety, which require close collaboration between PD developers, researchers and teachers (Guskey, 2002). Second, new practices tend to be abandoned if there is no evidence of their benefits for students, which makes providing feedback to teachers essential to the success of PD efforts (Guskey, 2002). Finally, since change in teacher attitudes and beliefs occurs primarily after implementation of a new PD program or innovation, ongoing follow-up, support and pressure are crucial to success of efforts. Support combined with "nudging" helps mitigate anxiety, pressure "is often necessary to initiate change . . . [and] to persist in the challenging tasks that are intrinsic to all change efforts" (Guskey, 2002, p. 388).

STEM professional development. STEM professional development programs should leverage what is known about science PD more generally. In general, this includes a focus on substantive issues of practice, embedding PD within teacher practice, be ongoing, and involve CoPs (Loucks-Horsely, et al., 2010). In addition, attention to the arenas of the Model of Teacher Change described above. However, PD programs aimed and developing understanding of STEM curriculum and pedagogy also have unique needs specific to integrated STEM. For example, STEM-based PD should offer opportunities to learn how to integrate engineering design into instructional practice, focus on problem-solving and analysis of prototypes developed by students, and offer opportunity and training for teachers to develop their own STEM curriculum (Avery & Reeve, 2013). STEM is unique because it encompasses multiple subject areas and pedagogies. Unlike most PD that focuses on one subject or strategy, STEM PD includes development of integrated approaches for teaching and creating STEM curriculum, for articulating a philosophical focus, for promoting integration of engineering technology, and honing engineering habits of mind analysis (Avery & Reeve, 2013).

The Teacher-Curriculum Relationship

In chapter 1, I presented a definition of curriculum materials as a course of study that includes different types of curriculum and educational experiences. I also defined curriculum as having four basic elements: establishing learning objectives, selection of learning activities, organization of learning activities, and assessment of learning objectives. In this section I will elaborate further upon conceptions of curriculum, implications for its use, and on involving teachers in the process of curriculum development.

Whereas in the 1990s curriculum use was theorized with a clear delineation between curriculum developers and teacher's roles interacting with curriculum materials (Remillard, 2005), greater collaboration with teachers on reform-based practices has contributed to changing conceptions of curriculum, and the teachers' role in curriculum use and development.

Conceptions of Curriculum

The recommendations for greater teacher involvement in education policy was one of several that coincided with a growing recognition that curriculum is more than the text within curricular materials. Curriculum is the embodiment of cultural "values and ideologies of teachers, policymakers and scholars" (Rosiek and Clandinin, 2016, p. 293). As such, curriculum is not simply a tool for student learning, it is also conceived of as a cultural tool that influences and is influenced by use (Brown, 2002, 2009).

Curriculum as a tool of mediated activity. *Mediated activity* refers to interactions between humans, the environment, and human-made tools (Kozulin, et al., 2003). Mediated activity refers to the meaning making processes that enable human development through interactions with "artifacts, tools, and social others" in an environment that results in new meaning (Yamagata-Lynch, 2010). Figure 2.3 is a recreation of how Vygotsky represented the human-environment interactions with what is often the Mediated Action Triangle (Cole & Engeström, 1993).

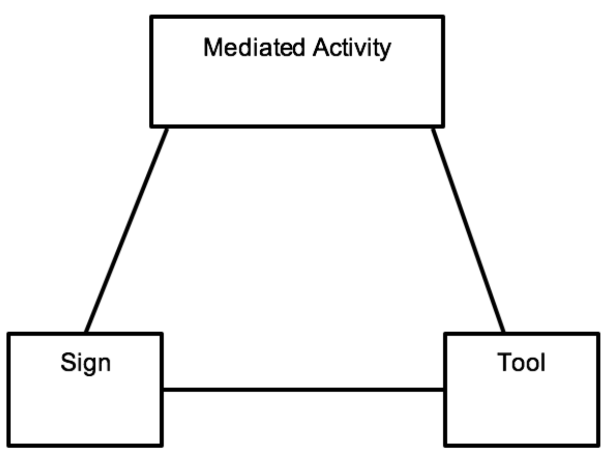


Figure 2.3. This figure illustrates the interrelatedness of humans, the environment and cultural tools that mediate activity.

The Mediated Action Triangle depicts human activity as a process that involves human-environment interactions, where artifacts that act as tools [external tools] and signs [internal tools] available in the social environment (Brown, 2002, paraphrasing Wertsch, 1993). The process of human activity interacting with tools within the environment is important for understanding mediated activity because the interactions contributes to individual cognitive development (Yamagata-Lynch, 2010). Individual learning and development is mediated by social interactions (Yamagata-Lynch, 2010). It is worth noting that there is not a specific moment when “an artifact transforms into a cultural tool, but a cultural tool is an artifact that has gained value within participants’ activities” (Yamagata-Lynch, 2010, p. 17).

If teaching is conceived of as a design activity where curriculum is a tool teachers use to craft instruction, then understanding curriculum also necessitates understanding its use and the factors that mediate how it is used. From this perspective, individuals, the use of curriculum, and the context of interactions, “are inextricably bound up in their use of cultural and physical tools” (Brown, 2009, p. 19). A curriculum embodies a range of possibilities for learning depending upon how teachers handle the curriculum materials available to them. At the same time, a teacher brings to the act of curriculum use a range of knowledge, skills, goals and beliefs that influence what aspects of the curriculum they use and emphasize. In addition, the context in which learning takes place influences the decisions they make in planning, implementing and assessing curriculum goals. These mediating aspects of curriculum inform and influence curriculum use and development.

Conceptions of Curriculum Use and Development

The emphasis on externally prepared curriculum materials to promote improvement of teacher practices is a common strategy used in reform efforts; yet, many see it at "reminiscent of the curriculum reforms that took place during the late 1950s and early 1960s" (Remillard, 2005) when experts 'worked on' rather than 'worked with' teachers (Ward & Tikinoff, 1976). In a review of the mathematics literature, Remillard (2005) identified several conceptions of curriculum and its purposes that are relevant for non-mathematics curriculum.

Multiple purposes behind curriculum use. As ideas about the nature of curriculum materials have evolved, the question of how teachers interact with curriculum materials has become relevant to understanding curriculum (Remillard, 2005). Remillard found four broad conceptions of curriculum, each with corresponding assumptions and theoretical stances that influence curriculum use (p. 217):

Curriculum Use as Following or Subverting the Text

Curriculum Use as Drawing on Text

Curriculum Use as Interpreting Text

Curriculum Use as Participating with Text

These different conceptions of curriculum and its use describe the differential degrees to which the teacher is an active participant in curriculum design. They also reflect differing theoretical stances about the teacher-curriculum relationship in terms of the agency of the text (curriculum) as a resource for instruction, and the agency of the teacher to influence and be influenced by curricular resources -- the degree to which the teacher brings their professional expertise and imagination to bear on crafting instruction.

The various stances related to agency assigned to the curriculum and the teacher frame what has been called the 'teacher-curriculum relationship' (Remillard, 2005). The different types of curriculum use form a spectrum where, on one extreme is the view that curriculum materials are "fixed" and the teacher's role is that of "enactor" of planned curriculum (*Following or Subverting the Text*), at the other extreme is the view that there is a "participatory relationship influenced by both teacher and curriculum" (*Participating with Text)*. In between these extremes teachers are active designers of enacted curriculum (*Drawing on Text)* or meaning makers where they draw upon their beliefs and experiences to make meaning of curriculum materials (*Interpreting Text)*.

Teachers as curriculum designers. The perspective that curriculum reflects values and beliefs has led to a shift in thinking about the role of teachers as being more than users of curriculum. Teachers act as "user-developers" (Connelly & Ben-Peretz, 1980), tapping their professional judgement to discover the 'curriculum's potential' and transform curriculum materials (Ben-Pertez, 1991). The notion of curriculum as fixed and the teacher as implementer has not gone away completely. However, there is a growing research body that considers teachers as legitimate designers of curriculum due to the fact that they act as designers as a regular part of their practice as they modify curriculum materials for their particular teaching context.

Teachers act as curriculum designers as part of their regular practice (Beyer & Davis, 2012; Brown, 2002, 2009; Brown & Edelson, 2003; Remillard, 2005). This happens naturally as teachers plan, implement and assess student learning, adapting externally prepared materials available to them. Partly teachers naturally act as designers of curriculum out of necessity because external curriculum developers cannot anticipate how every teaching context differs with regard to student needs and interests, teacher interests, goals and abilities, or school culture. Partly it is simply inevitable that teachers act as designers of curriculum (Brown, 2009; Brown & Edelson, 2003, p. 1):

- curriculum materials play an important role in affording and constraining
- teachers' actions;
- teachers notice and use artifacts differently given their experience, abilities; and
- teaching by design is not a conscious choice but an inevitable reality.

This perspective moves beyond the traditional notion that curriculum is simply used as is by teachers. Rather, curriculum use is a process of interpreting, evaluating and adapting to meet the needs of their classroom (Beyer & Davis, 2012; Brown, 2002, 2009; Brown & Edelson, 2003).

In addition to the theoretical conceptions of curriculum and the variables that influence curriculum use by teachers in general, STEM curriculum has unique features that influence use. Some of them I have described in my discussion of reimaging STEM PD -- engineering design, integration, and engineering habits of mind related to problem-solving. Another important factor unique to integrated STEM learning environments is that STEM is relatively young as a K-12 education goal. Therefore, STEM curriculum is relatively scarce compared to other types of science curriculum. As a result, STEM curriculum either needs to be written or existing curriculum adapted to reflect cross-disciplinary connections between the STEM disciplines and ensure that engineering and technology are represented.

Approaching the design of STEM curriculum as we have historically done, through "expert" curriculum developers is one approach. Another approach to STEM curriculum development is to use what we know about the importance of collaboration between teachers, policymakers and researchers to develop STEM curriculum as partners. Engaging teachers as curriculum designers has benefits and challenges. Benefits of engaging teachers as curriculum designers include: (i) taps into their expertise related to students, teaching context, and experience; (ii) aligns with goals described earlier for embedded and ongoing PD. (iii) if organized within CoPs, it provides a strategy to support teacher learning through legitimate peripheral participation; (iv) develops teacher buy-in and ownership.

Undoubtedly there are other context-specific and unanticipated benefits, especially if there is supporting STEM PD that aligns with the Teacher Change Model arenas for effective professional development programs. The primary challenge is that teachers have not typically been trained as curriculum developers (Huizinga et al., 2014) and though "curriculum design" and "curriculum development" are complementary, they are not completely analogous processes. Curriculum design refers to the ways in which we arrange the curriculum components. Curriculum development includes curriculum design expertise, but is defined more broadly, including the expertise to enact a curriculum design process, the knowledge and skills related to enacting the design process, and skills for curriculum development (Huizinga, et al., 2014).

Remillard (2005) has identified three arenas of curriculum development: the *design arena*, the *construction arena*, and the *mapping arena* (Remillard, 2005, p. 225):

- The *design* arena involves selecting and designing tasks and activities . . .

- The *construction* arena involves enacting these tasks in the classroom and responding to students' encounters with them . . .
- The *mapping* arena involves making choices that determine the organization and content of the mathematics curriculum over the year.

The design and construction arena have direct applicability to classroom tasks, whereas the mapping arena is not directly related to daily classroom events (Remillard, 2005).

In their work providing PD for STEM curriculum, McFadden (2015) and McFadden and Roehrig (2017) found that teachers working in teacher design teams defaulted to the *design* arena, selecting and designing tasks in a manner consistent with their existing classroom practices, rather than using reform-based strategies associated with integrated STEM curriculum. Applying Remillard's (1996, 1999, 2005) arenas of curriculum mapping to analyze teacher design team activity, McFadden (2015) and McFadden and Roehrig (2017) found teachers remain in the *design* arena without support that pushes them into the *mapping* arena.

In summary, while teachers regularly interpret and use curriculum to better meet the needs of their students as part of their regular practice, and work as curriculum designers to do so, they have not typically been trained to think as curriculum developers and require assistance to move between the arenas of curriculum development.

Conceptual and Analytic Frameworks

Overview of PDC and the DCE Analytic Framework

In his dissertation, Brown (2002) theorized the teacher-curriculum relationship in terms of design activity and highlighted the dynamic relationship between teachers and their materials, providing three constructs for understanding this relationship. The first contrasts offloading, adapting, and improvising provides a way to think about how teachers appropriate curriculum materials. The second construct, the Design Capacity Enactment framework (DCE), describes a framework for examining interactions between teachers and curriculum resources that influence decisions to offload, adapt or improvise curriculum materials. The third construct, was pedagogical design capacity (PDC), which he described as a teacher's "ability to perceive and mobilize existing resources in order to craft instructional contexts" (p. 24). Brown described the relationship between PDC and DCE as what he referred to as the *how* and *what* of PDC (p. 452):

> Pedagogical design capacity (PDC) provides a way of evaluating how individual teachers perceive and mobilize the instructional resources described by the Design Capacity for Enactment framework. While the framework provides a means for describing the resources that influence teachers’ use of materials, pedagogical design capacity characterizes their skill in interpreting and working with such resources. In other words, while the DCE framework accounts for the “what” of instructional capacity—that is, the subject matter knowledge, pedagogical content knowledge, goals, and beliefs that influence practice— PDC describes “how” such facets are used.

Taken together, the concepts provide a way of understanding the *process* of curriculum use (Brown, 2002). Rather than focusing on outcomes such as teacher or student learning, PDC development is concerned with understanding the resources teachers draw upon to craft instruction, and how those resources interact (Brown, 2002, 2009).

Offloading, Adapting and Improvising

A curriculum embodies a range of possibilities for learning depending upon how teachers handle the curriculum materials available to them. For example, when a teacher uses curriculum materials they must decide what content should be covered, what should be left out, what should be emphasized, and what must be modified (Ben-Peretz, 1990). To describe the teacher-curriculum relationship, Brown (2009, 2002) built upon the idea of teachers acting as 'user-developers,' (Ben-Peretz, 1990, quoting Connelly & Ben-Peretz, 1980), and the teacher's role as one of discovery -- discovering the 'curriculum potential' by transforming materials and using their professional imagination to develop curricular innovations (Ben-Peretz, 1990). Brown (2009, 2002) described the teacher-curriculum relationship in terms of the interplay of curricular and personal resources -- recognizing and drawing upon resources to craft instruction. One of the outcomes of his work was identification of three categories of how teachers use curriculum.

Offloading, adapting and improvising are important constructs for curriculum use both practically and theoretically. Practically, they provide a vocabulary for describing how teacher use curriculum. Offloading is characterized as following the curriculum materials with relative fidelity. Adapting is characterized as using curriculum materials in a manner that preserves the core ideas, but the teacher introduces modifications. In his dissertation, Brown (2002) uses the example of how a teacher adapted the lab set-up, making is less procedural, as proscribed by the curriculum guide, and more inquiry-based to align with her regular classroom practice. Improvising is characterized by the use of curriculum materials in a manner that relies more on the teacher's ideas and uses the curriculum more as a cue or a source of ideas from with to introduce significant modifications. Brown gave the example of a teacher improvising a classroom debate regarding the Earth-Sun relationship to deepen her students' understanding of the roles that angel of light reaching the Earth's surface and distance from the sun play in the Earth's climate. While the curriculum materials provided a starting point -- a journaling activity -- the debate was not planned, but improvised when the teacher capitalized on classroom events.

From a practical perspective, a common vocabulary for describing the ways teachers use curriculum supports collaborative curriculum development between teachers, policymakers, and researchers. It also has the potential to raise teachers' awareness of the ways they use their personal goals, beliefs and knowledge to modify curriculum materials. Greater awareness can help teachers make productive modifications to existing curriculum materials.

The constructs of offloading, adapting and improvising also have theoretical value, because they reflect the degree of agency assigned to the curriculum materials and to the teacher's own knowledge, experience and ability. Offloading assigns agency to the curriculum, adapting reflects shared agency, and improvising assigns agency primarily to the user of the curriculum materials (Brown & Edleson, 2003).

Theorizing the relationships between teachers and curriculum is important because it provides an alternative to quantifying student or teacher outcomes (learning, attitudes, etc.) as a strategy for understanding curriculum and instructional expertise. Theorizing the teacher-curriculum relationship in terms of identifiable patterns of use provides a way of analyzing curriculum design as a process (Brown, 2002). Offloading, adapting and improvising are informed by DCE framework -- the "what" of instructional capacity PDC -- the "how" resources that influence practice are used.

Design Capacity Enactment Framework: The *What* of Curriculum Use

The DCE framework illustrates the relationships between curriculum resources and the personal resources teachers bring to the process of designing instruction. The DCE framework also provides a way of evaluating interactions between curricular and personal resources to influence decisions teachers make to offload, adapt or improvise curriculum (Brown & Edelson, 2003). The DCE framework identifies two categories of resources that teachers draw upon for curriculum use, each with related types of resources that influence decisions for offloading, adapting and improvising. The two umbrella categories of resources teachers draw upon for curriculum use are: curricular resources and teacher resources. Curricular resources refer to core ideas, activities and physical objects that support instructional and learning activity within curriculum (Brown & Edelson, 2003). Teacher resources refer to the dispositions, abilities and motivations that teachers bring to instructional design (Brown & Edelson, 2003).

Each resource category has three subcategories. The categories of curricular resources reflect different facets of representations within the curriculum: Physical Objects (representations of objects), Procedures (representations of tasks), and Domain Representations (representations of concepts) (Brown, 2003). Physical objects refer to the material nature of the curriculum, such as a curriculum guide. Procedures refers to how tasks are represented, such as the scripts provided for teachers and students. Domain representations refer to the ways content is represented, such as visuals, graphs or models. Figure 2.4 provides an overview of the DCE framework.

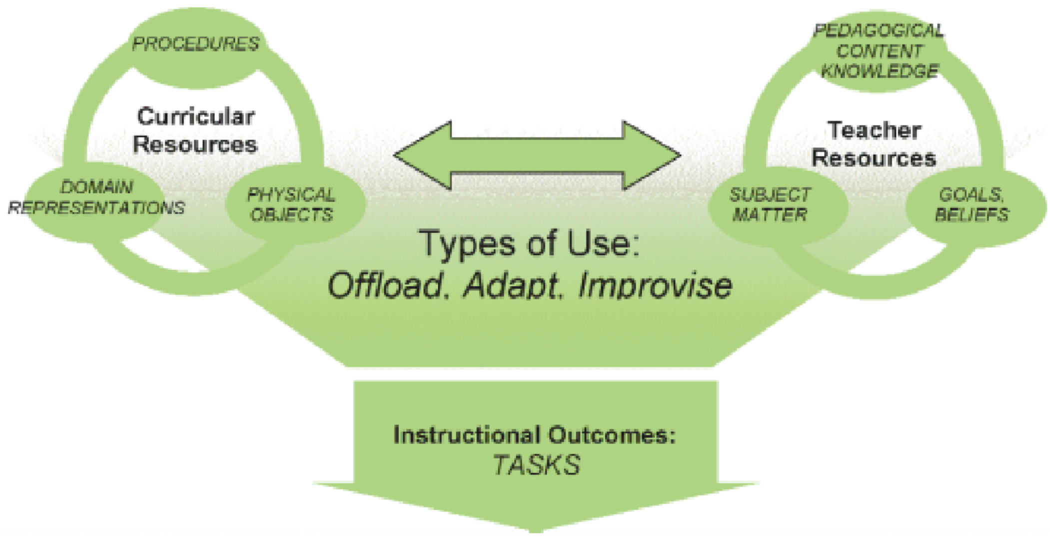


Figure 2.4. This figure shows the DCE framework. From *Teaching and Design: Can we Better Understand the Ways in Which Teachers Use Materials so We Can Better Design Materials to Support their Changes in Practice?* (Brown & Edelson, 2003, p. 4).

Each category represented within curricular and teacher resources is characterized by a specific type of resource. For example, subject matter is a resource that is distinct from pedagogy (PCK), even though all of them qualify as teacher resources. Besides the obvious distinction between curriculum and teachers, the two resource categories are distinguished by their physical and intellectual nature. The curricular resources take physical form (or representations of physical objects such as a ruler). The teacher resources are characterized by their "intellectual" or "psychological" nature (Brown, 2002, p. 48). While they take different forms, they both serve as tools teachers draw upon to craft instruction in their daily work. Table 2.1 describes each resource category, as they will be important for understanding the analysis in chapters 4 and 5.

Table 2.1. *Resource Categories and Subcategories of DCE Framework and Descriptions*

Category/Subcategory	Description and Example
Curricular Resources	Physical tools (rulers, stopwatches, teacher guides, etc.)
Physical Objects and Representations of Physical Objects	Curriculum binders as a means of transmitting content (graph template, data table, etc.) Representations of physical objects (materials lists, blueprints for assembly, etc.)
Representations of Tasks (Procedures and Scripts)	Directions for teachers and students (step-by-step procedures) Cues for teachers (divide students into groups, have students generate a hypothesis) Sequencing of activities (scope and sequence)
Domain Representations	Visual diagrams, models, descriptions of phenomena, etc.
Teacher Resources	Domain-general knowledge of teaching subject matter (general strategies, scripts, rules of thumb for managing students)
Pedagogical Content Knowledge	
Subject Matter Knowledge	Knowledge of subject matter (facts and concepts)
Teacher Goals and Beliefs	Teachers' beliefs about the nature of learning and student capabilities (individual and social)

A teacher's personal resources categories include: Subject Matter Knowledge, Pedagogical Content Knowledge (PCK), and Goals and Beliefs. Subject matter knowledge refers to a teacher's understanding of content. PCK (Shulman, 1986, 1987) refers to how teachers relate content-specific knowledge to their pedagogical knowledge to their subject matter knowledge. Goals and beliefs is a general category that includes instructional goals, ideology, cultural norms, values and habits (Brown, 2009).

The purpose of the DCE framework is to provide an analytic tool to understand trace interactions between curricular and personal resources (Brown, 2009), and understand how interactions between curricular and personal resources result in offloading, adapting and improvising curriculum (Brown, 2009; Brown & Edelson, 2003). PDC develops as the resources are transformed, adding to a teacher's repertoire of tools for instructional use (Brown, 2002; Brown & Edelson, 2003). The framework provides a tool to understanding the intersection between teacher practice, curriculum use, and the factors that influence them.

Applying the DCE framework. Brown (2002) applied the framework in a case study that followed a small group of teachers' use of a 10-week curriculum entitled the Global Warming Project. His analysis showed how offloading, adapting and improvising the curriculum reflect a "pathway" through the DCE framework (Brown, 2009, p. 28). In other words, offloading, adapting and improvising are reflections of interactions between curricular and teacher resources. Because offloads, adaptations and improvisations are a reflection of the resources drawn upon, they vary by teacher and even by classroom. A teacher may make a different decision for use of the same curriculum based on the dynamics of a particular group of students. For example, use of a curriculum at the beginning of the school year may be used in a more procedural manner at the beginning of the school year than towards the end of the school year. The DCE framework accounts for the *what* of the teacher-curriculum relationship, and PDC accounts for the "*how"* of the teacher-curriculum.

Pedagogical Design Capacity: The *How* of Curriculum Use

PDC refers to a teacher's ability to perceive affordances of curriculum materials (Brown, 2009) and is exemplified by teachers' capacities to mobilize personal and curricular resources to craft instruction (Brown, 2002, 2009). PDC develops through instructional activity as teachers draw upon curricular and personal resources to design instruction (Brown, 2002, 2009; Brown & Edelson, 2003; Beyer & Davis, 2012), and is distinct from (but related to) offloading, adapting and improvising (Brown, 2009). PDC is the process of weaving together the various pieces of the classroom, "the manner and degree to which teachers create deliberate, productive designs that help accomplish their instructional goals" (Brown, 2009, p. 29). Teachers offload, adapt or improvise curriculum materials for a variety of reasons including to "address particular student needs, to conform to certain teaching styles, to target specific learning goals, to align with classroom circumstances" (Brown & Edelson, 2003, p. 5).

Curriculum design as a process. Understanding curriculum use is typically approached by attempting to measure quantifiable outcomes (Brown, 2002). For example, changes in teacher understanding of content or pedagogy, changes in instructional practices or student learning. Conversely, PDC situates curriculum use in teacher practice. Situating curriculum use in teacher practice means professional growth is derived from a wide array of activities beyond formal schooling including classroom instruction, lesson planning, developing assessments, and collaboration with colleagues (Davis & Krajcik, 2005).

PDC development is premised on two main ideas: (1) teaching is a design activity; and (2) curriculum is a tool that promotes learning as a process (Brown & Edelson, 2003). PDC targets the *process* by which teachers grow their instructional expertise by focusing on the curricular and personal resources teachers use to inform curriculum use decisions. Because PDC develops through practice, and is characterized by perceiving and mobilizing resources to craft instruction, it explains both similarity and variations in curriculum use across teachers (Brown, 2002, 2009).

How teachers use curriculum materials depends upon several factors including how they understand the written curriculum as they read it, what is included in it, how it is organized, and the teaching context (Remillard, 2005). In the process, teachers develop more sophisticated ideas and are able to apply their knowledge to new situations as they make connections between their existing knowledge and new ideas (Davis & Krajcik, 2005). As teachers design, revise or implement curriculum, they naturally begin to reflect and draw upon their knowledge and experience, and incorporate their ideas into the new curriculum design (Brown, 2009). In this sense, the curriculum "serves as a cognitive tool to help teachers make connections between general principles and specific instructional moves" (Davis & Krajcik, 2005, p. 7).

PDC is a process where the relationship between perceiving and mobilizing resources shapes and is shaped by instructional activity. As teachers use curriculum, they see how students respond to and become familiar with key concepts and ideas within the curriculum materials, and in doing so, their repertoire of available resources expands. The process of drawing upon curricular and personal resources leads to the development of more sophisticated ideas and abilities as initial resources are transformed into new resources (Brown, 2002). Because PDC is dependent upon interactions of personal and curricular resources, it differs depending on the knowledge, skill and dispositions a teacher brings to their curriculum use (Brown & Edelson, 2003), and therein lies its ability to account for differences and similarities in teacher practice across different teachers and contexts (Brown & Edelson, 2003).

Taken together, the DCE framework and PDC explain variations in curriculum use and the resource interactions that drive them, and illustrates an important aspect of pedagogical design capacity -- that it emerges over time, rather than being manifested in any particular moment one can pinpoint. The ability to recognize affordances within curriculum materials and utilize resources to craft instruction is sometimes a one-time effort. Other times, the process requires “figuring it out” (Brown, 2009, p. 30). In these instances, figuring it out means growing familiarity with curriculum materials and accessing the personal resources to imagine and create productive ways to use the materials.

STEM PDC Development

Though PDC has never, to my knowledge, been studied in the context of STEM curriculum, this study is premised on the notion that STEM PDC, like PDC in general, develops through practice. Decisions to offload, adapt, or improvise STEM curriculum are, therefore, treated as a function of the degree to which there is alignment between teachers goals and the goals of the STEM curriculum materials. Also similar to curriculum in general, STEM PDC is influenced by the curricular resources embodied in the STEM curriculum, and the personal resources teachers draw upon to design and use the curriculum. However, in this study, STEM PDC differs slightly from the original application of PDC. The STEM curriculum in this study was developed by teacher design teams, not external curriculum developers. In addition, curriculum use in the classroom is not the primary focus of PDC development. Rather, the focus in this study is on post-implementation sessions where evaluation and redesign of STEM curriculum was the topic of collaborative conversations. As such, the focus of STEM PDC development is on how teacher design teams’ understanding of integrated STEM curriculum evolved.

PDC has typically been applied to individual teachers but teachers also work collectively. As such, applying PDC to teachers' collaborative work on curriculum design makes sense for understanding how STEM PDC develops across teacher design teams. Teacher learning and professional development is often approached from the perspective of individual teachers, but teachers do not work in a vacuum, they participate in communities of professional practice (Borko, 2004), use curriculum that reflects cultural values and beliefs to anchor their practice (Brown, 2002), and share common professional identity around their work (Wenger, 1998). The perspective that teachers work collectively for the purposes of professional development, plays an important role in in this study, in that development of STEM PDC is conceived of as a team *process*, where coming to understand STEM curriculum is built into the evolution of their collective ideas about STEM curriculum, the resources they draw upon (curricular, personal, protocol), the social interactions among the team members as they select, modify, and the contextual factors that inform and influence the process of coming to understand STEM PDC. Since *EngrTEAMS*, the broader PDP, structured the curriculum development process in cohorts of teacher design teams, it is helpful to situate it in the research authentically within the group.

Theoretical Framework

Theories on Curriculum Development

The curriculum development literature is vast, but can be distilled into three broad umbrella theories: Positivist, Critical, and Pragmatist (Rosiek & Clandinin, 2016). Each of these theories carries with it underlying notions about how people learn. Positivist theory is organized around producing curriculum knowledge through experimental trial, critical theory is organized around producing curriculum through ideological critique, and pragmatist theory is organized around producing curriculum knowledge through, "intra-action of human and non-human agents" (Rosiek & Clandinin, 2016, p. 297).

Pragmatism aligns with the view of the "teacher-curriculum relationship" (Ben-Peretz, 1990) as "participatory" (Remillard, 2005) that I described earlier. Pragmatist theory of curriculum development views knowledge as co-constructed through "ordinary experiences" such as daily planning and modifying curriculum materials as sources of knowledge and insight (Rosiek & Clandinin, 2006, p. 297). From a pragmatist paradigm, teachers acting as "curriculum makers" takes place on multiple levels and is informed by the following assumptions (Rosiek & Clandinin, 2006, p. 297-299):

> First, it affirms that ordinary experience – in this case the ordinary experience of teachers – can be an important source of unique knowledge . . .
>
> Second, pragmatism emphasizes the inclusiveness and continuity of experience . . . knowledge is not a representation that stands apart from our experience . . . knowledge is one more form of experience . . .
>
> Third, pragmatism includes a politics that is grounded in respecting and listening to others as centres of experience (Dewey, 1916, 1988).

A logical extension of this conception of the teacher-curriculum relationship suggests that instructional quality is not solely measured through outcomes. Rather, quality is also responsive to process, and intimately connected to human experience – "the overall transformation it works in the life of each learner (Rosiek & Clandinin, 2016, p. 297). A pragmatist view of curriculum development aligns with a sociocultural theory of teacher learning and development, which informs this study.

Sociocultural Theory

Sociocultural Theory is concerned with how people form reasoning as they participate in established cultural activities (Cobb, 2007), and has its foundation in Vygotsky's theories of learning. Vygotskian theory rests upon the idea that learning develops through mediating tools – language, schooling, learning activities, culture, etc. (Kozulin, 2003). For Vygotsky language drives learning, as does social environment. As learners appropriate cultural tools – social interactions, language, cultural norms, etc. – that serve as mediators of what is learned (Kozulin, 2003).

Vygotsky's theory has two basic components relevant to this study: The Zone of Proximal Development (ZPD) (learning potential) and Mediation of Learning (through human and cultural tools) (Kozulin, 2003). According to Vygotsky, learning occurs within the ZPD, where the ZPD is defined as the difference between the actual development level and potential achievement level of an individual. What he means by this is that learning takes place in the zone between what the learner can do independently and what they can only accomplish with guidance from what he refers to as the "more knowledgeable other" (MKO) (Vygotsky, 1978, p. 84). MKO refers to anyone who has more understanding or higher mental function than the learner. This can be a teacher, adult, peer, younger person or even a computer. As the learner discusses a problem or task with the MKO, the MKO supplies language to assist learner. The learner gradually internalizes the new information. An essential feature of learning is that it creates the ZPD; that is, learning awakens a variety of internal developmental processes that are able to operate only when the child is interacting with people in his environment and in cooperation with his peers.

A sociocultural theory of learning is premised on three conceptual themes: "cognition is: (a) situated in particular physical and social contexts; (b) social in nature; and (c) distributed across the individual, other persons, and tools" (Putnam & Borko, 2000, p. 4). A sociocultural perspective on education conceives of learning as being promoted through engagement in socially meaningful activities (Wenger, 1998) and involves a movement from social context to individual understanding (Mortimer & Scott, 2003; Vygotsky, 1978). The sociocultural view of learning is in contrast to the view that intelligence is innate, and to many formal learning experiences where everyone is learning the same thing and individually accountable.

Sociocultural theory is a useful framework for understanding teacher learning and development because it does not attempt to separate the social aspects of learning and development from individuals (Rogoff, 2008). This is particularly relevant for education research because teaching is a social act, taking place in classrooms with groups of people, through activities that are social in nature, that rely upon language and other cultural tools. Thomas, Wineburg, Grossman, Myhre and Woolworth (1998) have summarized the benefits well (p. 23):

> Individual teachers . . . bring with them very different areas of expertise, some are extremely knowledgeable about subject matter, whereas others bring specialized knowledge of students and students enrolled in Special Education programs. Teachers also bring different pedagogical understandings and expertise to the group discussion. By drawing on each

> individual's private understandings, which represent these different degrees of pedagogical and disciplinary expertise, the collective understanding of the group is thus advanced.

Given the fact that the sociocultural perspective recognizes teachers bring different knowledge and skills to social activity provides a theoretical framing that is authentic to the practices of teaching and learning, because it recognizes that human learning and development is a social and cultural, rather than individual phenomena (Kozulin, et al., 2003). The primary issues of interest related to understanding how STEM PDC develops during collaborative reflection and refinement of STEM curriculum include: (1) mediation; and (2) the perspective that learning and development are process- and context-dependent.

Mediation

Sociocultural theory informs and frames STEM PDC development, conceiving of teacher professional learning and development as taking place through a process of coming to understand of STEM curriculum mediated through interactions between cultural tools (curriculum), the environment (social interactions) and individuals (teacher knowledge, skill and beliefs). In this conception, curricular tools, social tools, and the tools teachers develop through teaching experience serve as resources for developing new insights and understandings. One aspect of teacher professional learning and development is, therefore, an evolving understanding of STEM curriculum.

Mediation as a concept central to sociocultural theory refers to indirect action through cultural tools (Yamagata-Lynch, 2010). As previously discussed, Vygotsky (1978) conceived of mediation as interactions between humans and their environment.

Human action with the world is mediated by both physical and psychological tools, the most important being language (Vygotsky, 1978). Mediation is a reciprocal process whereby tools influence and are influenced by social activity (Brown, 2002), and can also be directed inward (Vygotsky, 1978). In other words, mediation is a process of appropriating cultural tools to influence mental activity (Brown, 2002, paraphrasing Wertsch, 1998). For Vygotsky, all mental function takes place on two planes, on a social level and on an individual level (p. 163):

> Any function in the child's cultural development appears twice, or on two planes. First it appears on the social plane, and then on the psychological plane. First it appears between people as an inter-psychological category, and then within the child as an intra-psychological category. This is equally true with regard to voluntary attention, logical memory, the formation of concepts, and the development of volition. We may consider this position as a law in the full sense of the word, but it goes without saying that internalization transforms the process itself and changes its structure and functions. Social relations of relations among people genetically underlie all higher functions and their relationships.

A consequence of mediation is that knowledge is developed through use and interactions, and is not something acquired, but is a process. "Knowledge as information versus knowledge as concept formation . . ." and the implication that learning and development is defined by "culturally and socially situated" experiences rather than developmental age or IQ (Kozulin et al., 2003, p. 2). Vygotsky did not conceive of learning as taking place by way of a direct transfer form teacher to student. Learning takes place as participants involved in social interactions compare and check their understanding as they rehearse their ideas (Mortimer & Scott, 2003).

Learning and development, within this mediation framework, views coming to greater understanding as being accomplished through “distributed literacy, in which a number of participants contribute to different aspects of one literacy action (Zozulin et al., 2003, p. 16). In other words, “mediation,” not “acquisition,” but serves as a model for learning and development (Zozulin et al., 2003, p. 17). Variations in mediation are “scaffolding, apprenticeship, and organization of learning activities” in social context (Kozulin, et al., 2003, p. 17). It is important to note that meaning is contingent on context, and the dialogic nature of meaning is not always obvious. The same exact words have different meaning depending on the unique circumstances surrounding their use (Brown, 2002). Thus, meaning making is a result of a dialog that involves individuals, social context, and cultural tools (Mortimer & Scott, 2003). Sometimes a dialog is played out verbally in a public context, whereas other times a listener may be silent but still taking in the conversation surrounding him/her and “equally engaged in the dialogic process of coming to understand” (Mortimer & Scott, 2003, p. 12).

Zone of Proximal Development

According to Vygotsky (1978), learning occurs within the Zone of Proximal Development (ZPD). The ZPD is the difference between the actual development level and potential achievement level of an individual. In other words, learning takes place in the zone between what the child can do independently and what they can only accomplish with guidance from what Vygotsky refers to as the More Knowledgeable Other (MKO).

MKO refers to anyone who has more understanding or higher mental function than the learner. This can be a teacher, adult, peer, younger person or even a computer.

For Vygotsky, learning occurs through language, arguing that ". . . language is the main tool for promoting thinking, development of reasoning, and supports cultural activities like reading and writing" (Vygotsky, 1978). As the learner discusses a problem or task with the MKO, the MKO supplies language to assist the learner. The learner gradually internalizes the new information. An essential feature of learning is that it creates the ZPD as where social and cultural tools, including other people, serve as resources that support learning. The concept of ZPD is applicable to this study because the group serves as a resource for one another, helping the group to accomplish what none of the individuals could accomplish alone.

Sociocultural Theory and Communities of Practice

Lave and Wenger (1991) built upon Vygotsky's ideas of learning and development in articulating the role communities of practice play in "apprenticing" participants into social activity through *legitimate peripheral participation*. Apprenticeship refers to participation in communities of practice, where newcomers learn the social and cultural tools of a practice (Lave & Wenger, 1991). Legitimate peripheral participation conceives of learning as "a process of participation in communities of practice, participation that is at first legitimately peripheral but that increases gradually to engagement and complexity" (Lave & Wenger, 1991, introduction). In other words, by participating in social activity one learns the "social language" of the community and gains expertise over time. Through legitimate peripheral participation the conventional notions of teacher learning are expanded to include personal identity as a practitioner, community member, and are related to a particular domain of knowledge (Lave & Wenger, 1991, Wenger, 1998). Wenger (1998) built upon their original work, more clearly articulating the distinguishing between communities of practice, and other groups. Following Lave and Wenger's perspective on the situated nature of learning, communities of practice are defined by three fundamental parts: the community, a shared domain of interest, and a shared practice (Wenger, 1998).

A sociocultural perspective on teacher learning and development through participation in communities of professional practice requires three fundamental parts: (i) ensure professional learning opportunities take place on a social plane through communities of practice; (ii) help teachers make sense of new ideas through discourse focused on substantive issues of practice; and (iii) support teachers in applying new ideas. Collectively, these components encompass both classroom practice as well as professional collaboration and evaluation and reflection of instructional practices.

Making ideas available on a social plane, helps individuals make sense of new ideas, provides opportunity to applying ideas, and constitute a "*public performance* on the social plane of the classroom" where the performance is "*staged"* and "*scripted"* (Mortimer & Scott, 2003, p. 17). Similarly, weaving together a Vygotskian and situated perspective, Mortimer and Scott's point is equally true of teacher learning and development. For teachers, the "performance" takes place in two social planes: the classroom where instructional ideas are rehearsed, and again within the community of practice where the ideas are shared and re-rehearsed with fellow practitioners. As the teachers share their practice with each other they also share stories from the classroom, discuss problems of practice, and many other aspects of instruction to improve knowledge and skills of practice. In addition, the "performance" can be conceived of as being "scripted" by the teacher through curriculum -- in selecting, adapting and evaluating curricular tools. As teachers plan and implement performance moments they draw upon curriculum for ideas, for procedures, and for subject matter to craft instruction (Brown, 2002). They also draw upon personal resources they bring to curriculum use (Beyer & Davis, 2012), their subject matter knowledge, their pedagogical repertoire, goals and beliefs (Brown, 2002). Finally, collaborative work related to reform-based ideas require support through professional development.

Sociocultural Theory, Protocols and Professional Development

Bringing together sociocultural theory in general, and a situated perspective specifically, conceptualizes learning as a process of knowledge construction through enculturation into professional practice (Borko, 2004). Borko (2004) applies Vygotsky's idea of mediated learning to professional development, emphasizing the interconnectedness of PD programs, teachers, facilitators of PD, and the context:

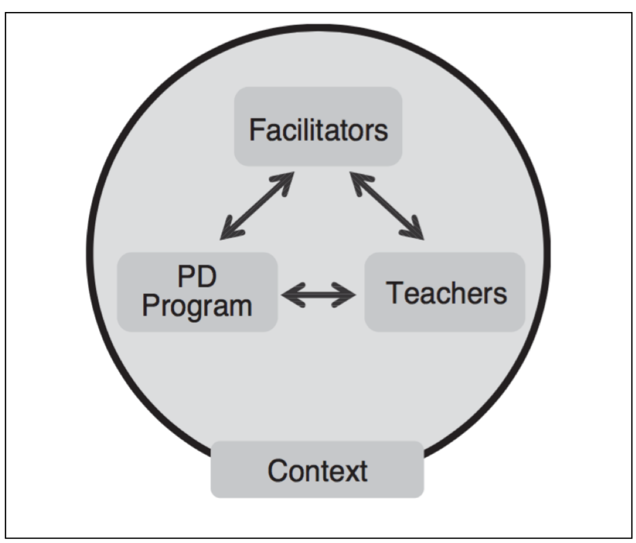


Figure 2.5. Elements of professional development from a situated perspective. From *Professional Development and Teacher Learning: Mapping the Terrain* (Borko, 2004, p. 4).

Consistent with a sociocultural perspective, teacher professional learning is mediated by a combination of human, environmental and cultural tools. Thus, attending to the context and tools used within PD programs is as important as the content of the PD. Protocols serve as tools that provide a way to facilitate the process and do so in a manner that honors individual ideas, experiences and the learning process.

Protocols

Protocols have been widely used to support education reform since the 1990s as a strategy to bridge the gap between educational organizations and teacher practice (McDonald, Mohr, Dichter, & McDonald, 2013). More specifically, as participation in professional CoPs became a common strategy for linking reform-based initiatives and teacher professional learning. Protocols provide tools that organize, scaffold and prompt group members while honoring the individual expertise and experience of participants.

A protocol is a set of agreed upon procedures to accomplish a task. Protocols are structured with prompts that focus the discussion on salient issues, set time limitations, and assign roles to ensure shared responsibility. The prompts establish norms, ensure equity of participation as well as individual accountability within a group structure (McDonald et al., 2013). By predetermining norms and assigning roles to group members, the authority to assess instructional outcomes belongs to all participants as does the task of working through "problems of practice" (McDonald et al., 2013, p. 8). National School Reform Faculty defines the purpose as: "a shorthand term for structured processes and guidelines that promote meaningful and efficient communication, problem solving, and learning" (http://www.nsrfharmony.org/, para. 1).

Since the 1990s when protocols were first introduced in education reform circles, a wide variety of protocols have been developed for different purposes, and have become a common strategy for facilitating CoPs. Though different protocols have different purposes, all share four basic principles: learning through constraints, learning from close textual analysis, practicing transparency, and "educating ourselves" (McDonald et al., 2013, p. 4).

Learning through constraints. The idea behind learning through constraints is that under the right circumstances, imposing constraints can teach three important skills (McDonald et al., 2014, p. 1):

> the first, how to give and receive safe and honest feedback; the second, how to analyze complex problems carefully and without rushing to judgment; and the third, how to ground interpretation of complex texts -- for example, student work or school data -- in close "readings" of the texts.

Unlike conversations that just unfold without predetermined guidelines, protocols are built around supporting the entirety of a collaborative conversation by attending to social interactions. By delaying judgment, for example, we learn to observe before making inferences and drawing conclusions.

Learning from close textual analysis. The use of classroom artifacts, be it data or student work, provides opportunities to think deeply about our practice, and use new insights and understanding to reflect upon how to improve, and provide feedback to others. Looking at student work in particular offers two important benefits (McDonald et al., 2014, p. 6):

> One is to learn more about the students' learning -- to gain clues about their strengths and weaknesses, their misconceptions, their proximity or distance from a conceptual breakthrough, their progress with respect to some defined standard, or their unique ways of thinking and working. And we read their work closely to appraise the efficacy of our own work.

Analyzing classroom artifacts involves more than "grading" student understanding, it involves revisiting our original intentions, how we communicate our intentions to students, and interrogates our own understanding of the content and skills we expect from students.

Practicing transparency. The final basic principle behind the use of protocols is tangentially related to learning from close textual analysis in that both help illuminate learning challenges for students, and serve to inform instruction. Protocols force transparency by intentionally dividing collaborative conversation into artificial boundaries. For example, when examining student work with protocols there is a boundary placed between individual and collaborative scoring of student work. By intentionally scoring student work in phases from individual to group, it creates points of dissonance and highlights points of agreement. If there is predetermined scoring criteria, which everyone in the group uses to score the work, then when members of the group come to different conclusions about the students' achievement of those criteria, the misunderstandings generate conversation aimed at the source of the misunderstanding.

Conversely, if everyone uses the criteria and draws the same conclusions, the criteria is probably pretty clear.

Educating ourselves. The benefit of structuring collaborative conversations to facilitate "educating ourselves" is it honors teachers as professionals by directing their education toward solving real problems educators face in their practice. Protocols value collegiality because, "our colleagues' values, standards, and methods are our business . . . and the problems of practice are inescapably mutual ones" (McDonald et al., 2014, p. 4). Protocols provide opportunities to learn from each other, and collectively solve mutual problems.

These four principles are at the core of their effectiveness for teacher learning, because they implicitly teach, "how to give and receive safe and honest feedback, . . . how to analyze complex problems carefully and without rushing to judgment; . . . and how to ground interpretations of complex texts -- for example, student work or school data -- in close "readings" of the texts" (McDonald et al., 2014, p. 1).

Protocols as a Tool for STEM Curriculum Development

There are an endless number of approaches to professional learning and development. Loucks-Horsley et al. (2010) have identified four categories: Immersion in Content, Standards and Research, Examining Teaching and Learning, Aligning and Implementing Curriculum, and Professional Development Structures (p. 167). Within each of these approaches to professional learning, there is a repertoire of strategies that are known to be useful depending on PD goals. The PD program in this study utilized a combination of immersion in STEM curriculum (Immersion in Content, Standards and Research), demonstration lessons (Examining Teaching and Learning), STEM curriculum implementation (Aligning and Implementing curriculum), and assigning graduate student coaches to each teacher design team (PD Structures). However, the coaching was left largely to the discretion of the graduate student coach and teacher design teams. As a result, sometimes the coaching conversations focused on substantive issues, other times they strayed to issues of housekeeping -- ordering materials, classroom behavior, etc.

To ensure post-implementation conversations focused on STEM curriculum development, this study introduced a *Looking at Student Work* protocol intervention. Later, in response to unanticipated events that took place during the protocol-guided sessions, the *Thinking Through a Task* protocol intervention was introduced. During the *Looking at Student Work* sessions the teams frequently had not predetermined assessment criteria, since the protocol proscribed a rubric, lack of assessment criteria rendered the protocol ineffective. The second protocol intervention was initially developed to address this problem, but was later utilized to facilitate the final curriculum redesign. I discuss the two protocol interventions at length in chapter 3, but it is useful here to understand the research on protocol use for teacher PD that informed the decision.

To my knowledge, the *Thinking Through a Task* protocol has not been studied within the context of teacher PD programs. However, variations of the *Looking at Student Work* protocol have been studied extensively and shown to be an effective strategy to support teacher learning and long term change in teacher practice. Demonstrated benefits of *Looking at Student Work* protocols include: teachers becoming more reflective of practice, identification and focus on goals, aligning student work with learning goals, emphasis on evidence, enhanced learning for participants, enhanced quality of assignments, and leadership development of participants (Loucks-Horsley et al., 2010).

In a study of 270 elementary teachers and 7,000 students, Heller, Daehler, Wong, Shinohara & Miratrix (2011) compared three teacher PD interventions: Teaching Cases, Looking at Student Work and Metacognitive Analysis. While Metacognitive Analysis did not show evidence of learning, *Teaching Cases* and *Looking at Student Work* improved teachers' and students' scores on pre-post measures beyond those of controls, and effects were maintained a year later.

In the following chapter, I discuss details of this case study methods, including further discussion about the specific protocol interventions used.

Chapter 3 : Methods

Physician, heal thyself.

Observer, observe thyself.

(Patton, 2002, p. 299, quoting Halcolm)

The goals of Chapter 3 are to articulate: 1. articulate the practical and theoretical decisions that led to the choice of a case study research design; 2. provide the reader with a clear sense of the study's goals and methods; 3. communicate the data collection procedures and analysis strategies. Chapter 3 is organized by first presenting a brief review of the study and its goals. Second, I present an overview of qualitative case study research design and rationale. Third, I discuss the methods utilized including a description of the participants, protocol interventions used during the study, and *EngrTEAMS*, the broader PD program this study was part of. Finally, I discuss data collection procedures, analysis processes, and study validity.

Review of Study and Goals

As discussed in Chapter 2, curriculum has been studied extensively because it is an important tool teachers rely on to plan, instruct and evaluate their instruction. Typically, the study of curriculum is approached from the perspective of how individuals construct meaning, or the contextual factors that shape curriculum assessment or pedagogy (Wyse, Hayward & Panda, 2016). This study of STEM curriculum differs from typical approaches. Rather than emphasizing outcomes for individuals, this study explores the process of STEM PDC development -- the teacher design teams' ability to identify and mobilize resources to craft instruction -- and the role two protocol interventions play in affording and constraining the process of PDC development.

Case Study Research Design and Rationale

Case study research can be described in terms of its in-depth examination of complex, real-world phenomena in a manner that is context sensitive (Patton, 2002; Yin, 2014), especially where the boundaries between the phenomena and the context in which it takes place may not be apparent (Yin, 2014). The goal of case study research design is to establish a logical pathway between the study's research questions, data, analysis and conclusions (Yin, 2014). In case studies, data is generally collected and organized with the goal of understanding a case *holistically* and in a manner that is *case sensitive* rather than with the goal of isolating variables and identifying individual outcomes (Patton, 2002, p. 447). The goal of case study research is to understand the complexities and processes of a phenomenon (Patton, 2002; Yin, 2014), often in situations that do not have clear boundaries between the phenomenon and context in which the study takes place (Yin, 2014).

In case study research, the case is the unit of analysis (Patton, 2002), and varies depending upon the participants and theoretical perspective of interest (Yin, 2014). Cases can be organized around individuals, groups, organizations or be bounded by events or "critical incidents" that illuminate and place boundaries around the research (Patton, 2002, p. 447). Bounding a case by events or critical incidents provides a way to focus on a phenomenon of interest, rather than the entirety of complex situations, and provides an analytic strategy to capture the richness of evens or experiences (Patton, 2002).

Because case study research is driven by the specifics of the case, “the term case study can refer to either the process of analysis or the product of analysis, or both” (Patton, 2002, p. 447). As a result, case studies take a variety of forms that fall under two broad umbrellas: single-case or multiple-case study design. Single-case research design allows for the study of unique cases with thick description of participants, their experiences and how they make meaning of their experiences (Yin, 2014). Multi-case research design allows for a more holistic approaches, which can be useful in cases where an explanation of the phenomenon of interest, causes and process is the primary goal of the study (Yin, 2014).

Rationale for Research Design

Patton (2002) advises qualitative researchers to select a research design method based on the fit between the phenomenon of interest and the underlying assumptions and principles of the method. Case study methods are appropriate when the researcher is interested in a complex topic that asks questions about people’s experiences and the meaning they make from them and, it is difficult to separate the phenomenon and its context (Patton, 2002; Yin, 2014). Case study is an especially suitable method when the researcher is interested in the processes behind a phenomenon (Mirriam, 1998). Case study suits this qualitative research study because the underlying assumptions of case study method allows for a sociocultural approach to analysis that does not attempt to separate the context from the phenomenon of interest. The goals of this study are to understand PDC development within collaborative teacher design teams, and the mediating factors that influence the process. Case study is a methodologically good fit with this study because it accommodates the social context within which STEM PDC developed for these teams, and recognizes that the researcher's role is not simply reporting what happened, but carries with it an interpretive and analytical voice present in reporting findings and the theoretical constructs the study was built upon.

The goal of this study is not simply to present findings, but to describe how the patterns and themes emerged from the data. One reason for selecting case study methodology is that PDC development is complex and socially situated within collaborative teacher design teams. In addition, the research questions dictated the choice of case study because their purpose was to both test existing theory about how PDC develops, using the Design Capacity Enactment analytic framework (DCE) that theoretically defines PDC development. I also had the goal of uncovering new theory specific to STEM PDC development and the role protocols play in affording and constraining STEM PDC development. The case study design was selected partly because of my sociocultural perspective on learning and development that conceives of learning as socially mediated, and wanting to describe the process, not simply the outcomes. In addition, the case study design was selected partly because the collaborative nature of the protocol-guided sessions made untangling the social context from the phenomenon of interest (PDC). The methods and, ultimately, the findings in this study seek to convey how patterns and themes emerged from the data, reflect the teacher design teams' experiences, knowledge and resources they utilized to inform the curriculum redesign process.

Purpose of the Study

The purpose of this study was to understand how teacher design teams engaged in co-development of STEM curriculum to grow their understanding of STEM curriculum, and the role protocol interventions played in the process. Prior to this study, no one had attempted to understand PDC development where the group was the unit of analysis, nor had anyone attempted to understand PDC within the context of the curriculum design process, as opposed to externally prepared curriculum.

As such, the study aimed to provide insights into this phenomenon and was guided by the following research questions:

1. How does STEM PDC develop in teacher design teams while examining student work and redesigning a co-developed curriculum?
2. How does the use of a protocol for examining student work afford and constrain collaboration and redesign of co-developed curriculum?
3. How does the use of a protocol for designing curriculum materials afford and constrain collaboration and redesign of co-developed curriculum?

Case Study Research Design Methods

Theory development prior to data collection is a defining feature of case study research design relative to other qualitative research methods (Yin, 2014). This case study will show how STEM PDC developed for three teacher design teams engaged in collaborative redesign of STEM curriculum and the mediating factors that influenced the process. It will also illustrate why protocols to guide collaboration and refinement of the curriculum and curricular tools are necessary for successful STEM PDC development.

This study was qualitative in nature and comprised of a multi-case study design. The multi-case study design was selected because it provides an approach that attempts to provide holistic explanation for the phenomenon of interest, in this case STEM PDC development, by analyzing individual cases, followed by cross-case analysis of the cases.

Multiple-case research design is a type of case study design that embeds multiple units of analysis within the overall case and context. The design builds into the study "the desire to analyze contextual conditions in relation to the "case" (Yin, 2014, p. 50), even when each case contains different groups within the overall case. In this multi-case study, three teacher design teams were embedded within the broader case and context of a professional development innovation -- co-development of STEM curricula -- in which cohorts of teachers developed, implemented, evaluated and redesigned STEM curriculum. Each teacher design team was its own case. The teams shared a common context, the professional development program.

Multiple-case research designs are considered more "compelling" and "robust" because they are likely to uncover findings that differ across cases and, thus, provide opportunity to see whether the findings from one case hold true in other cases (Yin, 2014). Thus, they provide opportunity to provide evidence "in the aggregate" that make for compelling support of initial propositions (Yin, 2014, p. 57). For example, in this study, the initial theoretical proposition is that protocols afford collaboration and refinement of the curriculum and are necessary for successful STEM PDC development. If all three cases support this proposition the findings can be considered more robust.

Context of the Study

This dissertation evolved out of a larger STEM reform PD program designed to engage teachers in planning, implementing, and evaluating integrated STEM curriculum. This study was conducted in conjunction with *Engineering to Transform Education of Analysis, Measurement, and Science in a Team-based Targeted Mathematics-Science Partnership (EngrTEAMS)* project. *EngrTEAMS* is a National Science Foundation (NSF)-

funded Mathematics and Science Partnership program. The program is a five-year, $8 million partnership between a major research university and K-12 partners across five districts. *EngrTEAMS* supported teachers in creating integrated STEM curricular units for each of the major science topic areas, informed by the Minnesota State Academic Science Standards for grades 4-8. *EngrTEAMS* offered teacher PD related to integrated STEM curriculum development aimed at improving student learning of science, engineering and mathematics (SEM) concepts.

The *EngrTEAMS* program combined summer PD with school year implementation supported with coaching during the school year. During an intensive three-week summer PD program, teams of teachers in grades 4-8 worked with a coach to co-design an integrated STEM curriculum unit. Each team worked with a graduate student coach who was enrolled in a STEM Ph.D. program. *EngrTEAMS* coaches helped teachers develop integrated STEM curricula, including curricular tools (rubrics, student handouts, etc.) and instructional practices related to STEM integration. During the school year, each teacher implemented the curriculum they co-developed and met with the coach monthly. The purpose of the monthly coaching sessions were set by the coach but informed by the teachers' needs. The content of the monthly coaching sessions took several forms, including helping to plan lessons, reflect upon implementation, engage in lesson study, and/or co-teaching.

Integrated STEM Professional Development Program

A primary goal of the *EngrTEAMS* was to expose teachers to integrated STEM curriculum, then provide teacher design teams the opportunity to engage teacher design teams in development of integrated STEM curriculum. For *EngrTEAMS*, integrated

STEM education was defined as an "effort to combine the four disciplines of science, technology, engineering, and mathematics in one class, unit or lesson, based on connections between the subjects and real-world problems," with the goal of ensuring learning is connected, meaningful, and relevant to learners (Moore et al., 2014).

EngrTEAMS was guided by a model of integration that used engineering as a context for problem-based learning that required the use of science and/or mathematics. The engineering design process (EDP) is central to the *EngrTEAMS* model of integrated STEM curriculum, as was articulating an engaging and motivating context for the engineering design challenge. The EDP is a systematic and iterative decision-making process in which science, engineering and mathematics (SEM) are used to design solutions to meet a need or solve a problem. *EngrTEAMS* established the context for the challenge and outlined the EDP with a client letter that provided the engaging context, and outlined the needs of the client, the criteria and constraints for the design challenge.

The three-week PD engaged teachers as learners, then gave them time to apply what they had learned to the development of an integrated STEM curriculum unit. The summer PD covered the following topics: data analysis and measurement, science-specific content (earth science, life science, physical science), the Understanding by Design (Wiggins & McTighe, 1998) curriculum development process, and participating in an engineering design process that modelled the topics covered. With these conceptions of integrated STEM in mind, the STEM integration model advanced during the *EngrTEAMS* PD followed the *Framework for Quality K-12 Engineering Education* (Moore et al. (2014). The framework emphasizes a conception of STEM where engineering provides the basis for STEM integration, and a guide for developing and evaluating important components of STEM integration (Moore et al., 2014).

Integrated STEM Curriculum Framework

In 2009, the NRC outlined three main principles for K-12 engineering education that included an emphasis on design, connections between science, technology, engineering and mathematics, and 21st Century Skills (systems thinking, creativity, collaboration, ethics, communication and several other things) (Moore et al., 2014). Moore and her colleagues developed the *Framework for Quality K-12 Engineering Education* to align with the NRC criteria. The Framework is a tool for developing and accessing integrated STEM curricula that was utilized during *EngrTEAMS* PD. The framework is organized around five key indicators: 1. integrated STEM curriculum should have a motivating and engaging context; 2. mathematics or science content should be integrated into the engineering design activities; 3. integrated STEM pedagogies should be student-centered; 4. students should participate in an engineering design challenge designed with a compelling purpose that requires problem-solving, creativity and higher-order thinking; and 5. Integrated STEM should emphasize teamwork and communication (Moore et al., 2014). Table 3.1 provides and overview of the aspects of the framework the teacher design teams emphasized, which was the focus of analysis (SEM, POD). For a review of the complete framework, refer to chapter 2.

Table 3.1. *Elements of the Framework for Quality K-12 Engineering Education the Teacher Design Teams Emphasized*

Key Indicator	**Description**
Complete Process of Design (POD)	Design processes are at the center of engineering practice. Solving engineering problems is an iterative process involving preparing, planning and evaluating the solution. Students should understand design by participating in each of the sub-indicators below.
POD sub-theme: Problem and Background	Identification or formulation of engineering problems and research and learning activities necessary to gain background knowledge.
POD sub-theme: Plan and Implement	Brainstorming, developing multiple solutions, judging the importance of constraints and the creation of a prototype, model or product.
POD sub-theme: Test and Evaluate	Generating testable hypotheses and designing experiments to gather data that should be used to evaluate the prototype or solution, and to use this feedback in redesign.
Apply Science, Engineering, Mathematics knowledge (SEM)	The practice of engineering requires the application of science, mathematics, and engineering knowledge and engineering education at the K-12 level should emphasize this interdisciplinary nature.

This study occurred during the third year of *EngrTEAMS*. Similar to the previous years, after the teachers completed the summer PD, the teams piloted portions of their curriculum to help them test and refine the curriculum further. During the school year each teacher implemented the STEM unit in their classrooms. Once each teacher on the team had implemented, the team redesign the curriculum, which was due June of 2016. Table 3.2 provides a timeline of *EngrTEAMS* activities that guided this research.

Table 3.2. Timeline of Research Activities and *EngrTEAMS* Professional Development Program by Case

Contrasting Cases	June-August 2015	Fall 2015	Spring 2016
Case 1 **Elementary (traditional)**	**3-week professional development** Co-design Curriculum Pilot Curriculum Draft 1	**Implementation** Matthew (Dec.) *Looking at Student Work* Matthew brings student work & rubric	**Implementation** Kathryn *Looking at Student Work* Kathryn brings student work & rubric
Case 2 **Elementary (co-teach)**	**3-week professional development** Co-design Curriculum Pilot Curriculum Draft 1	**Implementation** Co-teach (Nov./Dec.) *Thinking Through a Task* Team brings student work (Dec.) Co-designs rubric	**Implementation** Re-teach (Jan. & March) *Thinking Through a Task* Team brings student work & 3 iterations of assessment *Looking at Student Work*
Case 3 **Middle School**	**3-week professional development** Co-design Curriculum Pilot Curriculum Draft 1	**Implementation** Robert *Looking at Student Work* Robert brings student work & rubric	**Implementation** Amanda & Mark *Looking at Student Work* Mark brings student work *Thinking Through a Task* Co-designs rubric
***EngrTEAMS* Activity**	Coaches assigned to teacher design teams, materials for implementation ordered.	Coaches meet monthly with individual teachers	Coaches meet monthly with individual teachers
Research Activity	Interview participants	Post-implementation meetings with teams and facilitator	Post-implementation meetings and Curriculum redesign meetings with teams and facilitator, focus groups conducted

This study focused on the post-implementation protocol-guided sessions. As discussed in chapter 2, teachers often lack the expertise for curriculum design, and need support related to analysis, and evaluation, and curricular consistency of the curriculum (Huizinga et al., 2014). The study interventions, took the form of two protocols, and were utilized following each team member's implementation of the curriculum, and after all team members had implemented but before they re-wrote their integrated STEM curriculum. The first protocol, the *Looking at Student Work* protocol was designed to collaboratively examine student work resulting from the co-developed STEM curriculum. The second protocol, the *Thinking Through a Task* protocol, facilitated redesign of the curriculum. The interventions supported teachers with curriculum redesign in a systematic, yet open-ended manner.

Participant Selection

Participant selection proceeded through a systematic narrowing from a pool of 44 potential *EngrTEAMS* teachers. It was determined that only teachers from one district would be considered for participation, which narrowed the participants to 16 potential teachers. Since the study focused on elementary and middle school, the pool of teachers was further narrowed to 12 teachers. The potential participants agreed to participate, and these 12 teachers were interviewed. One team was later eliminated when they implemented simultaneously rather than sequentially, as dictated by the study design. Because the study dictated that teams meet following each teacher's implementation for feedback and reflection, the team implementing simultaneously could not participate in the protocol intervention sessions. Ultimately, seven teachers and three coaches participated in this study, grouped into three teams, two elementary, and one middle school team. The teams reflect contrasting cases: contrasting elementary and middle school, and contrasting teaching structure, with one elementary team comprising "traditional" teachers who each has their own classroom and a second elementary team that co-taught an elementary STEM class. The names used in this study are pseudonyms.

Team DIY Stringed Instrument (DIY). Team DIY was comprised of two teachers who did not teach in the same school, and their coach (see Table 3.3). Kathryn taught 5th grade and was in her sixth year of teaching at the time of the study. She worked in a school where 68% of students qualify for free-or-reduced lunch. The student body is 39% African American, 35% white, 12% Asian, 11% Hispanic and 3% Native American. Matthew was a 2nd grade teacher is in his 20th year of teaching. He worked in a school where 70% of students qualify for free-or-reduced lunch. The student body is 56% African American, 25% white, 14% Hispanic, 3% Asian and 1% Native American. The team's coach, Kurt, was a former high school mathematics teacher with 18 years of 7-12 experience, and 6 years of experience at the college level (some of that time overlapped). This was his first year working on *EngrTEAMS* and his first coaching experience. Kurt's coaching style is best described as relationship-driven (Sweeney, 2015), where his role is to provide support for teachers in a manner that does not challenge them.

Table 3.3. *Team DIY Participants and their Roles Within the Teacher Design Team*

Name	**Experience**	**Position**	**Gender**	**Team Role**
Alexa	16 years	*EngrTEAMS*	Female	Facilitator
Kathryn	6 years	5th grade	Female	Participant

Kurt	20 years	*EngrTEAMS*	Male	Coach
Matthew	20 years	$2^{nd}/3^{rd}$ loop	Male	Participant

Team Powered by Renewable Energy (PbRE). Team PbRE was comprised of two teachers who co-taught a K-5 STEM class, and myself as the team's coach (see Table 3.4). Janice was in her 5th year of teaching and George in his 8th year of teaching at the time of this study. Janice was an elementary teacher with a degree in science and had taught both mathematics and physical science at the middle school level. George was an English Language Learner (ELL) who is fluent in Spanish. They worked in a school where 26% of students qualify for free-or-reduced lunch. The student body is 69% white, 21% African American, 6% Hispanic and 4% Asian. Though the school website does not breakdown the 21% African American further, a significant percentage of that number are Somali students. My role on this team was multifaceted because, besides being a colleague at the district and Team PbRE's coach, I also was facilitator of the protocol sessions. At the time of this study, I was a former high school science teacher with 16 years of PreK-16 teaching experience. Eleven years were spent teaching 9-12 science, and in the past 5 years at the college level teaching methods classes, and at the district level providing PreK-12 teachers with STEM professional development. This was my fourth year working on *EngrTEAMS* as a coach. My coaching style is best described as student-centered (Sweeney, 2015), where my role is to partner with teachers so it uses classroom artifacts to inform instructional plans.

Table 3.4. *Team PbRE Participants and Their Roses Within the Teacher Design Team*

Name	**Experience**	**Position**	**Gender**	**Team Role**
Alexa	16 years	*EngrTEAMS*	Female	Coach, Facilitator
Janice	5 years	K-5 STEM	Female	Participant
George	8 years	ELL	Male	Participant

Team Laser Security System (Team LSS). Team LSS was comprised of three teachers, and their coach. None of the teachers teach in the same school, but all teach 6th grade physical science (see Table 3.5). At the time of this study, Amanda was a 6th grade teacher in her third year of teaching and works in a school where 96% of students qualify for free-or-reduced lunch. The student body was 77% African American, 16% Hispanic, 3% Native American, 3% Asian and 1% white. Robert taught 6th grade physical science and was in his sixth year of teaching, and worked in a school where 79% of students qualify for free-or-reduced lunch. The student body was 50% African American, 26% Hispanic, 13% white, 9% Asian and 2% Native American. Mark was a 6th grade teacher in his fourth year of teaching and worked in a school where 81% of students qualify for free-or-reduced lunch. The student body was 52% African American, 19% white, 18% Hispanic, 6% Asian and 5% Native American. Jayd, the team's coach was a former high school physics and chemistry teacher with seven years teaching experience. This was her first year working on *EngrTEAMS* and her first coaching experience. Jayd's coaching style is best described as student-centered (Sweeney, 2015), where her role is to partner with teachers and use student-centered practices to inform instructional decisions.

Table 3.5. *Team LSS Participants and Their Roles Within the Teacher Design Team*

Name	**Experience**	**Position**	**Gender**	**Team Role**
Alexa	16 years	*EngrTEAMS*	Female	Facilitator
Jayd	7 years	*EngrTEAMS*	Female	Coach
Amanda	3 years	6^{th} physical	Female	Participant
Robert	6 years	6^{th} physical	Male	Participant
Mark	4 years	6^{th} physical	Male	Participant

My role as participant observer. My role was multifaceted as researcher, facilitator, and participant observer for all teams, and as the coach for one team. An important aspect of qualitative research is self-awareness and ownership of one's social and ideological perspective, because who the researcher is affects what they observe and how they understand what they observe (Patton, 2002). *Reflexivity* is the term that refers to the cultural, social, and ideological aspects of the researcher's perspective (Patton, 2002). For example, my own background and predispositions influenced both my interest in using protocol interventions to support development of STEM PDC, and my focus on STEM reform. When thinking about developing PDC with teachers, the facilitator has an influence because meaning is mediated and changed in the activity. The words, social interactions and content of the activity evolve through co-participation (Lave & Wenger, 1991). In addition, because I served as both a graduate student enrolled in a STEM Ph.D. program and as a district STEM leader, I have both expertise and collegial connections to the study participants. These roles further shape and are shaped by the participation.

I served as a facilitator for the protocol-guided sessions, and as the coach for one of the elementary teams (Team PbRE). As a graduate student, I had participated in coaching training, two Ph.D. graduate-level STEM education courses. The first course focused on STEM and STEM integration and was led by the co-principal investigator of the *EngrTEAMS* project. The second course was focused on a coaching model that utilized reflective practice (York-Barr, Sommers & Ghere, 2006), and aimed at coaching strategies that help teachers build their skills as curriculum developers and STEM teachers. As a participant observer I worked closely with Team PbRE as their coach, and with the other teams as a colleague in the district. I had did not have previous working relationships with any of the teachers prior to this study, though I did, through my district position as a STEM Integration Specialist, recruit all of the participants for *EngrTEAMS*.

Protocol Interventions

The protocol interventions were designed to structure collaborative conversations, and to maintain focus of conversations on student learning. The goal was to ensure collaborative conversations remained focused on salient issues related to integrated STEM curriculum. The protocols serve as interventions to support the teachers by facilitating productive curriculum redesign, collaboration, and focus coaching conversations on productive curriculum redesign. They are also intended to support teacher professional learning related to integrated STEM PDC. There were two protocols used to support the processes: one for examining student artifacts and one for redesigning the co-developed curriculum.

***Looking at Student Work* protocol intervention.** *The Looking at Student Work Protocol* was adapted from the *Standards in Practice Protocol* developed by Education Trust (edtrust.org). The protocol was originally developed in response to standards-based reform efforts in the late 1990's to facilitate alignment of education standards with learning tasks (Blyth, Allen & Powell, 2015). The adapted intervention protocol was developed in response to science reform efforts to facilitate integration goals for integrated STEM content and pedagogy. As each teacher implemented the curriculum unit, they collected student work that represented a range of student success levels with the engineering design challenge. At the collaborative examination of student work session the presenting teacher shared the student work he/she collected, and the rubric he/she planned to use to assess the work.

The *Looking at Student Work Protocol* structured and focused collaborative team coaching sessions. Following each team member's implementation, and before the next team member implemented, teachers discussed the learning goals of the assignment and what students must know and be able to do for success on the assignment. Next, each teacher individually scores each piece of student work. When each teacher has scored each piece of student work, the team compares and contrasts scoring decisions. When there were differences in scoring a discussion takes place where teachers discuss their understanding of the rubric and cite evidence within the student work itself to come to consensus about how to score the work. Finally, the team reflects on the student work, the assignment, and the clarity of expectations reflected in the rubric to inform the next teacher's implementation planning.

The overall goal for the protocol-guided intervention was to serve an iterative function, informing the teachers understanding of the effectiveness (or lack thereof) of their instructional decisions and support ideas for redesign of curricular tools (student instructions, the rubric, etc.) and curriculum (approaches, strategies, etc.). Once all teachers had implemented the team came together before rewriting the final curriculum.

***Thinking Through a Task* protocol intervention.** *The Thinking Through a Task Protocol* was adapted from the *Thinking Through a Lesson Protocol* developed by the School of Education at the University of Pittsburgh (Blyth et al., 2015). The protocol was originally developed to guide teachers in lesson planning instruction aligned with student supports and assessment (Blythe et al., 2014). The purpose of the adapted intervention protocol was to expand the focus of collaborative conversations beyond examination of student work, and to explicitly take curriculum redesign into consideration. The rationale behind this intervention strategy was to support collaboration during the curriculum design process, revisit original learning objectives, and avoid a "divide-and-conquer" strategy for curriculum design.

Like the *Looking at Student Work* protocol, the *Thinking Through a Task* protocol focused on the engineering design challenge component of the curricular unit. Also like intervention one, the protocol structured and focused collaborative team coaching sessions and informed the teachers understanding of their instructional decisions. The *Thinking Through a Task* intervention differed because it took a broader perspective considering factors related to curriculum design rather that classroom-level issues such as goals, in-process support, modifications and assessment. Once all teachers had implemented, a final team coaching session took place to initiate rewriting the final version of the co-designed curriculum. Teachers once again discussed what students must to know and be able to ground the conversation, then they discussed in-process support such as how to support use of academic language, questioning strategies and specific content and skills to provide students. Finally, the team discussed assessment, and how to support integration of mathematics and/or science to solve the engineering design challenge and next steps.

Data Collection and Analysis

Case study research "constitutes a specific way of collecting, organizing, and analyzing data" that involves organizing data by cases for in-depth study (Patton, 2002, p. 447). Generally, qualitative case study research relies on multiple types of observational and/or interview data, and analysis of the data can be inductive, deductive, or both. In cases where theory development is the goal, inductive strategies are especially useful, whereas deductive strategies support goals where theory confirmation is the ultimate goal (Patton, 2002). This study relied on several types of data, and utilized both inductive and deductive analysis strategies. The analysis centered around content and thematic analysis of cases, which led to several assertions supported with critical incidents (Patton, 2002) to bound analysis activity provide insight into particularities and complexities of the larger case. In the following section I first discuss data collection, followed by a detailed description of the analysis cycles and their corresponding purposes.

Data Collection

Data collection for this study took place during the summer of 2015 and the 2015-16 school year. The data included: (1) *Looking at student work* audio/videotaped sessions following each teacher's implementation of the curriculum; (2) *Thinking through a task* audio/videotape sessions during the final curriculum redesign session; (3) two versions of the curricular artifacts co-developed by each team, the first draft (summer 2015) and the final draft (spring 2016); and (4) focus group interview of participants.

Collection and transcription of post-implementation protocol-guided conversations was conducted in the following manner: (1) Videotaped conversations were uploaded to a secure, online server; (2) Video files of the protocol-guided sessions and focus groups were transcribed by me, whereas the interviews were transcribed by an outside transcription service (audiotranscription.org); (3) Transcripts were uploaded to a data management software program (MaxQDA); (4) All transcripts were analyzed using inductive and deductive coding cycles. A description of the coding analysis procedures will be discussed in the analysis section.

Protocol-guided conversations. Videotapes of the *Looking at Student Work* and *Thinking Through a Task* protocol-guided sessions served as the study's primary data source. There were a total of eight *Looking at Student Work* sessions, each 50 minutes to one hour in length. The sessions were guided by predetermined protocol prompts, and facilitated by me, the researcher and participant observer. See Appendix for protocols and their respective prompts.

The protocol-guided sessions began with Team DIY (Case 1), and were transcribed in the order in which the teams implemented. Case 1 began with Matthew implementing first, followed by Kathryn within a week of Matthew's implementation. The next team to participate in the *Looking at Student Work* sessions was Team PbRE (Case 2). Team PbRE co-taught, so their implementation and examination of student work cycles differed slightly from the other teams. Rather than implementing by teacher, the team implemented by class. The team implemented with one class, then we met for a *Looking at Student Work* session. The team then implemented with a second class and met for a *Looking at Student Work* session, which culminated in a final implementation and *Looking at Student Work* session. Team LSS (Case 3) was the final team to implement and participate in the *Looking at Student Work* sessions. Implementation began with Robert, followed by Amanda, and culminated with Mark's implementation. Because neither Robert or Mark attended Amanda's session, the session was not included in this study. Finally, the *Thinking Through a Task* session for each team took place after all teachers had implemented and participated in the *Looking at Student Work* sessions, but before they redesigned the final curriculum.

Curricular artifacts. The co-designed curriculum and curricular tools served as secondary data and include: lesson plans and instructional tools (rubrics, student materials) and the curriculum unit as a whole. The final curriculum units and classroom artifacts were uploaded to the secure server by the *EngrTEAMS* coaches.

Focus group. Focus group data served as a secondary data source. The focus group was conducted after all protocol-guided sessions had taken place. The focus group was an hour and a half in length, and questions focused on collaborative curriculum design, examination of student work, and working collaboratively. Table 3.6 lists the focus group questions.

Table 3.6. *Focus Group Questions*

	Focus Group Questions
1.	Engineering Teams is really about having teachers design STEM curriculum. Tell me about some things you are proud of in your curriculum.
2.	Tell about your experience working in teams this summer designing curriculum. Note: make sure pros and cons come out, if they don't, ask follow up question.
3.	What resources did you draw on during the curriculum development process? Note: If their answer about time or materials, then ask if anyone else drew upon other types of resources.
4.	How did you consider the specific nature of your school and classroom in this experience?
5.	What, if anything, is the value of looking at student work in relation to curriculum redesign to improve curriculum?
6.	What, if anything, is the value of looking at student work in a group, rather than individually?
7.	What, if anything, is the value of structuring our meeting with a protocol for looking at student work?
8.	We did multiple iterations of looking at student work. In what ways did this process inform your implementation of the curriculum?
9.	What ideas did you hear from others that you wouldn't have thought of on your own?
10.	What did you learn about yourselves as curriculum designers?
11.	What is the take-always from this discussion with other teams?

Analysis Goals and Methods

This study concerned understanding how collaborative teams of teachers grow their understanding of STEM curriculum and the factors that influence it. According to Saldaña (2013), such questions are epistemological in nature and justify coding strategies that provide insight into knowing and understanding the phenomena of interest. To this end, inductive analysis strategies were used to unveil patterns and themes within each case that reflect the ideas and experiences of participants, followed by deductive analysis to confirm findings and align them with my research questions and the literature on pedagogical design capacity. Finally, a cross-case analysis was performed to synthesize the emergent patterns and themes across cases.

To stay open to what the data revealed and not move too quickly to the predefined codes related to the DCE framework, I used a combination of First Cycle of Coding strategies recommended by Saldaña (2013) to describe the data. In order to develop a more complete sense of the thematic, conceptual and theoretical ideas present in the data, I used analytic coding strategies during the Second Cycle Coding process to re-coded the data. Finally, cross-case analysis was used to compare the ideas and experiences of participants reflected in the data, with the goals of confirming and developing theory related to development of PDC.

First Cycle Coding Goals and Methods

For the first cycle coding process I used a combination of Initial Coding and Holistic Coding. I began the coding process using a combination of Initial and Holistic Coding because the case study research design had the goal of both staying open to the data to develop new theory specific to STEM PDC, but also to confirm existing theory related to what is known about how PDC develops using analytic categories within the DCE framework. Thus, I wanted to consider differences in the data that were unique features of this study and could not anticipate in advance.

Initial Coding. Initial coding (Carmaz, 2014; Corbin & Strauss, 1967, Saldaña, 2013) is also commonly referred to as Open Coding (Charzaz, 2014), and has the goal of remaining open to possibilities within the data. Initial coding is an approach intended to provide a starting point from which the researcher can uncover “analytic leads for further study” (Saldaña, 2013, p. 101). Initial coding (Saldaña, 2013) is consistent with constructed grounded theory (CGT) Charmaz (2014), where the researcher may start with existing coding scheme but proceeds to move beyond the initial coding scheme through a process of “constant comparative analysis” (Corbin & Strauss, 2008, p. 73). As the analysis evolved so did the analysis codes. Each concept in the data is coded for a category that is a label for a concept. As the concepts were coded, I compared them with the existing concepts coded in the same categories to find similarities differences in the data (Glaser, 1965), which allowed me to hone my descriptions of the category and identify sub-categories. As the codes properties and dimensions began to emerge, a second round of coding was conducted, Holistic Coding.

Holistic Coding. After an initial review of the data, Holistic Coding (Saldaña, 2013) was applied to the data. Holistic coding is a strategy for “chunking data” into broad topics, and is appropriate when the researcher has an idea of what they are looking for in the data (Saldaña, 2013, p. 142). I used holistic coding to prepare for the second cycle analysis, setting aside data that was not pertinent for answering the research questions. Because I already knew of the literature-defined aspects of PDC development -- patterns of curriculum use (offloading, adapting, improvising) and the resources that influence them -- I used holistic coding to develop preliminary patterns and identify preliminary themes, and aligned them with the design capacity enactment (DCE) analytic framework defined in the literature. I also identified preliminary themes not previously associated with the DCE framework, but relevant to the study's research questions. Thus, I preserved new, emerging theory related to STEM PDC development and confirming theory related to PC development in general.

Content analysis at the end of the first cycle coding process led to several patterns and themes in the data. In addition, there were unanticipated patterns in the data. I use the terms "pattern" and theme" in the manner described by Patton (2002): The term *pattern* usually refers to a descriptive finding, for example "almost all participants reported feeling fear when they rappelled down the cliff," while a theme takes a more categorical or topical form: *Fear"* (p. 253). The identification of patterns and tentative themes led to a second cycle of coding, where the goal was to deductively make connections between the data and analytic framework.

Second Cycle Coding Goals and Methods

The first cycle coding was comprised of an iterative process of looking for patterns in the data that related to PDC development and the factors that affected it. These codes included topically and theoretically informed patterns, with the goal of remaining open to what the data meant. The second cycle coding involved moving from an inductive process of looking for what is in the data, to a deductive process that aligned with the PDC literature in general, and components of the DCE framework that defines PDC. To achieve the goals of refining my understanding of what I was uncovering in the data, a combination of Focused Coding (Saldaña, 2013), followed by Pattern Coding (Miles & Huberman, 1994; Saldaña, 2013). The Second Cycle Coding process helped me to take large segments of data coded according to topic and refine them into conceptual categories and isolate components of the DCE framework (curricular resources, teacher resources, and offloading, adapting and improvising).

Whereas First Cycle Coding was largely descriptive in nature, Second Cycle Coding utilized comparing, conceptualizing and categorizing the data to reflect emergent ideas and experiences of the participants and align them with the DCE framework. To accomplish these goals, I use Theoretical Coding (Charmaz, 2014; Corbin & Strauss, 2008; Saldaña, 2013).

Theoretical coding. Theoretical coding is an umbrella code that accounts for theoretically focused analysis (Saldaña, 2013). The purpose is to synthesize previously assigned categories and specify relationships between categories (Saldaña, 2013).

Theoretical coding is appropriate in cases where the goals it to apply existing theory to new situations in order to address the "how" and "why" of a phenomena (Saldaña, 2013, p. 224). Research that applies pre-existing theories has unique qualities, though it also seeks to generate new theory. "Research that applies pre-existing theories in different contexts or social circumstances, or that elaborates or modifies earlier theories can be just as substantive" (Saldaña, 2013, p. 224). To build new theory from existing theory it is essential to "address the "how" and "why" questions that explain the phenomena in terms of "how they work, how they develop, how they compare to others, or why they happen under certain conditions [Hennick et al., 2011,] pp. 258-277)" (Saldaña, 2013, p. 224).

I utilized the DCE framework to guide the process of theoretical coding, taking a more deductive stance, and hone my preliminary themes further. At this point the goal was to reduce the number of codes and reorganizing codes into more thematic units of analysis. To accomplish these priorities, I took the descriptive codes from my earlier analysis and merged the similar ones together, creating a "meta-code" from which to make assertions about what the data means, as recommended by Saldaña. I also refined and redefined the properties and dimensions of the codes where necessary.

Upon completion of second cycle coding all three cases had been analyzed, and the findings for each case were compiled. Before transitioning to writing up the findings, a transitory step was conducted to focus findings and gain a deeper understanding the nuances within the themes.

Theoretical Assertions and Critical Incidents

The analysis process generated several codes and exemplar data for each team that illustrated the patterns and themes in the data for each case. However, the analysis was over 100 pages long and included narrative descriptions of the protocol-guided sessions. To further define the theoretical assertions additional analysis was conducted to refine and focus the findings. In situations where the analysis results in large amounts of findings, focusing strategies are called for. Focusing strategies are recommended by Saldaña (2013) as a post-coding and pre-writing transitional analytic process between coding and final write-up of the study.

Focusing Strategies

Focusing strategies help to prioritize the ideas that emerged throughout the analysis by reflecting on the essential meanings. The coded data was further analyzed and critical incidents selected that illustrate representative themes and "existentially problematic moments" (Patton, 2002, p. 129, quoting Denzin, 1989b), where the teacher design teams grappled with problems they encountered with their co-developed curriculum, and possible solutions to curricular problems.

To begin my focusing process, I first selected segments of data from the protocol-guided sessions that struck me as the most illustrative of STEM PDC development and/or the role protocols play in affording or constraining the process. These segments of data were labelled Critical Incidents (Patton, 2002). Second, for each critical incident, I made an assertion that encompassed the essential meaning of the data segment. Saldaña (2013) refers to taking the most salient outcomes of qualitative data as "codeweaving" (p. 248). Codeweaving is a technique for translating codes into "narrative form to see how the puzzle fits together" (p. 248). To understand how the puzzle of my multi-case study fit together, I arranged my assertions and supporting critical incidents by case, and reflected on the content of each critical incident, searching for evidence that informed the assertion. Finally, using the assertion as a topic, I wrote a narrative analysis for each critical incident to prepare for the individual cases for cross-case synthesis.

Cross Case Analysis

Qualitative cross-case synthesis of case studies is necessary to build upon the body of knowledge generated from analysis of individual cases (Cruzes, Dybå, Runeson, & Höst, 2015). Thematic synthesis is a cross-case analysis strategy that embodies making a "new whole out of the parts" with the goal of generating unique concepts and interpretations of familiar issues (Cruzes et al., Introduction para. 5, 2015). This dissertation has simultaneous goals of developing curricular innovations (protocols) and analyzing the processes involved in their use for redesign of a co-developed integrated STEM curriculum.

Top begin my cross-case synthesis of the three individual cases, the assertions and supporting critical incidents were organized into a table that summarized and highlighted commonalities and variations across cases. These critical incidents were then aligned with the research questions and protocol interventions and a table created for each case. The next step was creative synthesis (Patton, 2002) of the individual cases with the goal of an holistic understanding development of STEM PDC. In other words, presenting the three cases as a complex system of cases that works together to provide analytic generalizability.

Analytic Generalizability

The goal of qualitative research is not to generalize findings, but to gain insights into the experiences of participants and processes of the phenomenon of interest (Yin, 2014). Analytic generalization refers to development of theoretical propositions to inform the design of the case that corroborate or otherwise advance theoretical concepts (Yin, 2014). In this study, the data collection methods and analysis strategies implemented resulted in theoretical assertions supported by critical incidents. These were used to both uncover new theory and corroborate aspects of the DCE framework. Chapters 4 and 5 present the findings and theoretical generalizations.

Validity and Reliability

In this study, construct validity was ensured by collecting multiple sources of data (protocol-guided sessions, focus group, curricular artifacts) and following a predetermined case study protocol for the protocol-guided sessions. In addition, my analysis was not arbitrary. The analysis was based on a systematic and pre-planned coding and analysis strategy. The systematic nature grounded the analysis in multiple checks on the interpretation to reflect and revise, as well as recheck the evidence guiding the interpretation. Finally, I used a multiple-case structure to provide reliability in that replication of the major patterns and themes across cases supports analytic generalizations (Yin, 2014). Using a variety of data sources, combined with multiple-case structure addresses both validity and reliability.

Limitations

The analysis process with the researcher being an informed observer introduces limitations and biases. However, the systematic collection and analysis of data and coding for facilitation strategies that make my researcher and participant transparent mitigate biases. In addition, the multiple iterations of analysis forced me to constantly reevaluate my interpretations, honing and refining them.

In the following chapter, I discuss details of this analysis, including further discussion about the specifics of each case analysis, and the development of analytic assertions and supporting critical incidents.

Chapter 4 : Individual Case Analysis

"Materials offer starting points, and teachers use their curricular insights, their pedagogical knowledge, and their professional imagination to develop their own curriculum ideas on the basis of existing materials" (Ben-Peretz, 1990, p. 52).

Organization of Chapter 4

This chapter is organized around three contrasting cases, Team Do-it-Yourself Stringed Instruments (Team DIY), Team Powered by Renewable Energy (PbRE) and Team Laser Security System (LSS). Team DIY was comprised of two elementary teachers and their coach – Matthew, Kathryn and Kurt (pseudonyms). The cases are presented in the order the teams began to implement. As such, Team DIY is Case 1, Team PbRE is Case 2 and Team LSS is Case 3. Each case is presented using the same structure starting with background information about the teachers' pre-STEM PD practices, their teaching context, and a description of the curriculum they co-created. This is followed by a description of the *Looking at Student Work* and *Thinking Through a Task* protocol-guided sessions. The data for each case is presented chronologically in the order the teacher design team participants implemented their curriculum.

The data from these collaborative sessions led to multiple assertions about: (i) the personal resources teachers bring to the curriculum design process (experiences, goals and beliefs about teaching and students, etc.); (ii) the curricular resources they drew upon (the *EngrTEAMS* PD, curriculum materials, books, etc.); and (iii) how interactions between personal and curricular resources mediated the ways in which the teachers used the curriculum (offload, adapt, improvise); (iv) how protocol-guided discussions about curriculum use influenced curriculum redesign; and (v) how multiple iterations of curriculum use followed by examination of student work mediated the process of STEM PDC development for each teacher design teams.

Before presenting my analysis, I present a brief reminder of the study's purpose, research questions, and a brief review of the Design Capacity Enactment (DCE) framework. Next, I provide a preview of the analysis to illustrate how I used the framework to understand PDC development and the role protocols play in the process.

Brief Review of Study Purpose and Research Questions

The analysis addressed in chapter 4 explores how STEM pedagogical design capacity (PDC) develops through participation in curriculum redesign, and the role protocol interventions play in the process. The chapter provides insights into how STEM PDC develops and how the protocol interventions afforded or constrained collaboration and refinement STEM curriculum. The purpose of this study is to understand STEM PDC, and the role that protocols play in affording and constraining PDC development during collaborative curriculum redesign. Three research questions guided this study:

1. How does STEM PDC develop in teacher design teams while examining student work and redesigning a co-developed curriculum?
2. How does the use of a protocol for examining student work afford and constrain collaboration and redesign of co-developed curriculum?

3. How does the use of a protocol for designing curriculum materials afford and constrain collaboration and redesign of co-developed curriculum?

Design Capacity Enactment Framework Review

I begin with a review of the Design Capacity Enactment Framework (DCE) (Brown, 2002; Brown & Edelson, 2003) described in detail in Chapter 2, that frames the analysis that follows. The framework illustrates the classes of curricular teacher resources that structure the analysis, and how resources interact to inform decisions to offload, adapt and improvise curriculum (see figure 2.4). Offloading, adapting, and improvising are distinct forms of curriculum use that result from interactions between resources.

Relationship of DCE Framework and PDC

The DCE framework serves as an analytical tool for understanding how teachers recognize and mobilize curricular and personal resources for instruction (Brown & Edelson, 2003), and provides a way of characterizing how various combinations of curricular and teacher resources influence teacher's capacity to design instructional activity (Brown, 2002). PDC is a term that describes the process of evolving knowledge and capacity to design instructional activity.

In the following section, I applying the framework to a portion of data from Team DIY's curriculum in order to illustrate how the Framework can be used to highlight interactions between personal and curricular resources, how those interactions influence curriculum use, and how the process transforms the teacher's instructional repertoire. The point being, to show the ways in which they expanded their knowledge and capacity to design instruction (Brown, 2002).

Sample Analysis Applied to Team DIY Data

In the following analysis, I build upon the discussion of the DCE framework by focusing on Lesson 1 of Team DIY's curriculum and comparing and contrasting how teachers reported offloading, adapting and improvising the co-developed curriculum during their *Looking at Student Work* sessions. Brown (2002) and Brown and Edelson (2003) articulated the DCE framework in relation to pre-existing curriculum materials. In this study, I use the framework in a slightly different manner. Brown (2002) and Brown and Edelson (2003) use offloading to refer to cases where the teachers assign agency to pre-existing curriculum materials, following them with fidelity. In my case, offloading refers to how closely the teachers follow their original co-developed curriculum materials.

Illustrating Offloading, Adapting and Improvising

My analysis of offloading, adapting, and improvising Team DIY curriculum is focused on how each teacher attended to the Engineering Design Process (EDP) and integration of mathematics into in *Lesson 1: Engineering Design Challenge*. Whereas Kathryn implemented the co-developed curriculum with relative fidelity, offloading it, Matthew significantly adapted and improvised ideas from the original curriculum related to the EDP and mathematics integration. These points of departure from the original curriculum became problematized during the *Looking at Student Work* sessions, and provide insights into the reasons for modifications they made (or did not make). They also provided insight into curriculum redesign process, and how STEM PDC evolved. The analysis used the following approach: (i) explore the protocol session data for reports of offloading, adapting and improvising, making note of the reasons given for decisions to offload, adapt or improvise; (ii) compare original and final versions of the co-developed curriculum, looking for adaptations and improvisations; (iii) select segments of data to serve as "critical incidents" that reflect patterns in the ways the team problematized and looked for solutions, which allows me to make assertions about curricular and teacher resources, collaboration and refinement of curriculum and the influence of the protocol interventions.

Sample Assertions and Supporting Critical Incidents

Sample Assertion 1 and Supporting Critical Incident

In the following sample critical incident, I illustrate how I conducted my analysis (see table 4.1). The critical incident illustrates how teachers make two differing classroom-level decisions about how to use the original curriculum, and how those modifications to the original curriculum are used during the protocol-guided sessions to gain insight into integrated STEM curriculum and how to redesign it.

Table 4.1. *Sample Critical Incident Related to the Engineering Design Process*

Assertion: Classroom-level modifications to the EDP inform curriculum redesign ideas during the protocol-guided sessions.
Critical Incident

Kathryn	Matthew
KATHRYN: We had them design it [the stringed instrument], and then we taught, and I had them redesign it [the stringed instrument] and we looked at their redesign during our protocol for *Looking at Student Work*. Seeing the improvement from their initial design to their final design, was huge. So I feel, being able to look at the student work and knowing where they started and where they ended was, I knew that project was a good one for them. **Later, during the focus group session she discussed the value of prototyping:** Well, I would do it [re-prototype] in a heartbeat. Having them redesign because I think it gives them an opportunity to take what they've learned from the unit and put it into their second design rather than just saying, 'I'm done!' Because nothing is ever perfect. . . No one was, 'oh, mine's perfect'! They all went to work to redesign.	**MATTHEW:** . . . Each day there would be a new problem that we would kind of talk about and so, how many of you are finding your instruments are collapsing? What do you think might happen inside an instrument to keep the top from falling down? Then we built some bridges. We talked about the slipperiness of rubber bands, so I said, 'what could hold it and in place?' So they said, 'we could tape it.' I go, 'What might happen if you tape it?' It's all those leading questions, but the fact that they're USING a why, or the fact that they're DRIVING this, the fact that they are PLANNING some ways to make pillars and supports inside, I think, would be a place where I would add to the rubric. **ALEXA:** So, did they do multiple iterations of this? **KURT:** No (laughing) **MATTHEW:** I would die **Later, during the same session he reflected on his experience:** **MATTHEW:** I learned a lot of lessons from this. Maiden voyage, I would say. **ALEXA:** You want to say any more about that? **MATTHEW:** Yeah. Ill-structured is one thing. There has to be enough structures so that it just doesn't turn into a complete disaster. It was structured enough, would be one lesson I've learned.

The critical incident illustrates how classroom-level decisions about how to use the original curriculum, one to offload and one to adapt the co-developed curriculum related to the EDP, and how those modifications to the original curriculum are used during the protocol-guided sessions. Despite having the same curricular resources

(*EngrTEAMS* PD, curriculum, etc.), Matthew and Kathryn reported significant variations in their approaches to implementation. These classroom-level individual modifications to the curriculum were discussed during the protocol-guided session and used to inform their ideas about integrated STEM and to redesign the co-developed curriculum.

Engineering the design process individually and collaboratively. Prior to this excerpt, both Kathryn and Matthew, offloaded the client letter, using it as originally intended. That is, they introduced the EDP with very little procedural structures, allowing the EDP process to be student-centered rather than providing all students with the same prototype parameters. The curriculum they had designed called for the unit to begin with students making stringed instrument prototypes, then they taught the mathematics and science content, and the unit culminated in the engineering design challenge where they re-prototyped. Whereas Kathryn continued to follow the co-developed curriculum with relative fidelity regarding multiple prototype iterations during the EDP, Matthew adapted the co-developed curriculum, dropping the second iteration of the prototypes. These were not chance decisions, they were driven by the curricular resources in the co-developed curriculum I just described, and the personal resources each teacher had available to them during implementation. Thus, the variations in curriculum use reflect their respective curricular and personal resources interactions.

Kathryn drew largely from the co-developed curriculum as written, implementing it as written, prototyping, teaching the content, then re-prototyping. Matthew, on the other hand, made the decision to adapt the co-developed curriculum by omitting the second iteration of the prototypes. While this critical incident does not speak to what triggered the decision, one topic that comes up subsequently, several times is the age of his students and the challenges of managing an ill-structured task for 3rd graders.

Adaptations to the scope and sequence reflects the Procedures aspect of the curricular resources, Matthew adapted the procedures within the prototype phase of the EDP, responding to problems managing materials that arose during prototyping, drawing on his personal abilities to recognize and address students' needs along the way by adding structure as students' experiences warranted. From Kathryn's perspective, having students prototype, then learn the content, followed by having the students re-prototype worked for her 5th grade students. She believed it provided an opportunity to apply what they learned to inform the prototype redesign.

During the *Looking at Student Work* session problems with the co-developed curriculum pushed the team's understanding of STEM curriculum related to the engineering design process (EDP) and integration of mathematics into the engineering challenge. The topics of the EDP and integration of engineering and mathematics received a significant amount of time and attention as that reflect their initial interpretation of integrated STEM curriculum, and their evolving understanding. In the process the teacher design teams used classroom-level modifications to inform their understanding of the EDP inform curriculum redesign ideas during the protocol-guided sessions. This is PDC development, growing their ability to recognize and mobilize resources, and expanding their repertoire of available resources to craft instruction.

Sample Assertion 2 and Supporting Critical Incident

In the previous sample, I demonstrated my analysis related to offloading and adapting the EDP. In the following, I illustrate improvising SEM integration.

Table 4.2. *Sample Critical Incident Related to Integration of Science, Engineering and Mathematics*

Assertion: Teachers address problems with the STEM curriculum by drawing upon personal knowledge and pedagogical skills developed through previous experiences.	
Critical Incident	
Matthew	**Kathryn**
MATTHEW: . . . I started with troubleshooting what could be potential problems . . . the flimsy cardboard could be a problem and duct tape sticking to it is always a problem ... Those are the little things that I could either pre-teach or you can catch them as they fall. So, I usually wait until the first one fell and then I just go, ‘Stop. Mini-lesson. Keep going.’ **From Matthew’s *Looking at Student Work* session**	**KATHRYN:** We had them design it [the stringed instrument], and then we taught, and I had them redesign it [the stringed instrument] and we looked at their redesign during our protocol for *Looking at Student Work*. Seeing the improvement from their initial design to their final design, was huge. So I feel, being able to look at the student work and knowing where they started and where they ended was, I knew that project was a good one for them. **MATTHEW:** When I was working on this with my third graders, I kind of let them try and fail a little bit and then, or if someone was starting to approach an idea we just stopped, kind of like Workshop Model, ‘Oh this is what I just noticed somebody doing,’ and then did mini-lessons on what a Net is.” **From Kathryn’s *Looking at Student Work* session**

This critical incident illustrates how teachers address problems with the STEM curriculum in a multi-step process. First, by sharing classroom experience, and how they drew upon personal knowledge and pedagogical skills developed through previous experiences. Second, by using insights from their own and each other's experiences during the protocol-guided session as resources to collaborate and refine their curriculum.

Matthew's *Looking at Student Work* session. This excerpt illustrates a strategy teachers utilized to address problems with the STEM curriculum by drawing upon personal knowledge and pedagogical skills developed through previous experiences. Throughout the design challenge Matthew negotiated the tensions between the original curriculum and the perceived to structure with pre-teaching to "catching them as they fall." On the one hand, this required structure and guidance on the part of Matthew to ensure learning goals are met. On the other hand, his approach is premised upon creating opportunities for students' ideas and projects to influence the direction of instruction. When Matthew refers to letting students work independently punctuated by "mini-lessons" as the need arose he is invoking a strategy similar to the Workshop Model (Calkins, 1983, 2003). Workshop Model is a strategy for differentiating instruction and facilitating independent "workshops." Generally, the Workshop Model is structured around a short independent work assignment, followed by a mini-lesson, which culminates in a review of the day's learning by focusing on the work of one or two students that use what was taught in the mini-lesson. Connecting this critical incident, to his description of his classroom in the interview data (from summer), Matthew's intervention strategy reflects his ability to draw upon a strategy he was familiar with to adapt the EDP structure. In the act of drawing upon his personal knowledge of Workshop Model to address the problem, he transforms the resource -- overlaying a Workshop Model-like structure onto the EDP. His use of mini-lessons serves to meet his dual goals of providing structure for his students and maintaining the student-centered spirit of the original STEM curriculum.

This critical incident also illustrates how Kathryn's contribution to the improvisation was not triggered by problems with the curriculum, but by recognizing how an unplanned classroom event presented an opportunity improve their curriculum.

Kathryn's *Looking at Student Work* session. Kathryn's observation that geometry was useful in her classroom and suggestion that it might be important to add to their list of what students need to understand, led Matthew to share that he also had taught nets. In Matthew's case, it was not a matter of recognizing the value of something he did previously, he improvised the co-developed curriculum with a "mini-lesson" on nets. The addition of "nets" to their curriculum took the form of teacher notes, rather than a full replacement of the budget criteria. Despite the fact that both teachers independently taught it and thought it was a valuable learning component of the STEM unit.

The topic first came up during the second protocol-guided session, when Kathryn responded to the prompt about what students need to know and do for success on the project. It just so happened that prior to her implementation of this unit, she taught a Geometry unit on "nets." A "net" in Geometry is a flattened out three-dimensional (2-D) shape such as a cube or a pyramid that is transformed into a 3-D form by cutting out the "net," folding it, and gluing it into a 3-D shape. Only after starting the design challenge did she realize that her prior instruction related to transforming 2-D representations into 3-D objects was helpful for her students during the project.

Geometry was not initially on the team's radar as a productive tool for developing student understanding of how mathematics can inform the design of a stringed instrument. Instead, the curriculum integrated mathematics by having students to keep a budget for the materials they used to build their instrument prototypes. It was through the protocol-guided discussions that the team shared their experiences, ideas, and honed their thinking about mathematics integration, and in the process, expanded their repertoire of resources available to them for redesign of their curriculum.

One of the basic tenets of PDC development is the ability of teachers to not simply recognize, but also to act upon curricular and teacher resources and bring them to bear on their use for the curriculum. How the teachers discussed the "nets" improvisation demonstrates that ideas from the classroom, when introduced into the protocol-guided sessions help the teams think differently about ideas, problems and solutions. In this case, not only do they recognized the mathematical value, but since they both actually taught it, they have the capacity to mobilize it and craft their instruction around it. The interactions between the teachers' personal knowledge of "nets" (Teacher Resource) was utilized to bring mathematics principles (Curricular Resources) to bear on the engineering design challenge. The manner and degree to which they acted upon their understanding of Geometry (personal resources) -- *how* they used the idea of Nets once they recognized it could be useful -- demonstrates their pedagogical design capacity (PDC). Furthermore, it illustrates how retelling stories from the classroom triggered information from other teacher design team participants. Despite the fact that the team had met before, and discussed at length alternatives to budget as a strategy for integrating mathematics into their STEM curriculum. The Kathryn's storytelling triggered Matthew's story. What was initially individual insights and curricular modifications in the classroom morphed into co-storytelling – co-constructing their ideas about mathematics-engineering integration.

Science, engineering and mathematics integration. Integration of science and mathematics into the engineering design challenge is a central tenet of integrated STEM curriculum. The way Team DIY achieved integration goals in their curriculum was through the science of sound (pitch, volume), and having students keep a budget to satisfy the mathematics requirement. The teacher design team addressed problems with the STEM curriculum when they recognized an opportunity to teach a geometry concept that would inform their students ability to design the prototypes using mathematics, rather than just "tinkering" until they got the protocol built. By learning a mathematical way to visualize and transform a 2D piece of cardboard into a 3D musical instrument, their knowledge of both mathematics and engineering is enhanced. In by drawing upon personal knowledge and pedagogical skills developed through previous experiences, the teachers improvised the original curriculum and improve it. They also grew their understanding of STEM curriculum specific to SEM integration, and STEM PDC.

Concluding Thoughts

Through augmenting their original STEM curriculum with new ideas, possible solutions to problems they encountered that the team's PDC evolved. Their decisions were initially influenced by their perceptions about the feasibility and authenticity of the aspects of their curriculum that they perceived as challenging (a reflection of their goals and beliefs), as well as their capacity to implement the EDP and integrate. During the protocol-guided sessions they grappled with reconciling their new insights about SEM integration into their curriculum.

In this section my purpose was to illustrate how the DCE framework supports analysis. My purpose was to demonstrate how curricular features and the protocol-guided discussion combine to reveal how PDC develops including: (i) incidents of offloading, adapting and improvising, even where not reflected in modifications to the STEM curriculum support STEM PDC development; (ii) show how variations in implementation of the co-developed curriculum are due to teachers capacity to recognize opportunities for improvement and respond to those opportunities by drawing upon their personal resources they have amassed from previous teaching experiences; (iii) how current curricular and teacher resources interact and transform the teachers' instructional repertoire; and (iv) how the individual teachers bring their problems and enacted solutions to the team where those ideas are shared, transformed, and distributed across the team resulting in evolution of STEM PDC for the TDT. In the following sections I look more closely at each TDT, analyzing each case, beginning with Team DIY.

In the following sections I provide narrative descriptions of each team, their curriculum, and do an in-depth analysis using the analysis approach just described with the illustrative examples.

Narrative Description of Case 1

In this section, I describe Team DIY and their curriculum in greater detail. First, I describe the team's curriculum. Second, I provide a description of how each team member described their implementation. Third, I provide an analysis of each team member's *Looking at Student Work* protocol-guided sessions, making a series of assertions related to my research questions supported with data from the sessions. Fourth, I provide an analysis of the team's *Thinking Through a Task* curriculum redesign session, also making a series of assertions supported with data from the session. Finally, I provide a summary of findings aligned with the study's research questions. Following is a short description of the integrated STEM unit, followed by a summary of each lesson within it.

DIY Curriculum: Physical Science – Sound and Light

In this thirteen-lesson unit, the students have been "hired" by Do-it-Yourself (DIY) Stringed Instruments, a toy manufacturing company. A client letter establishes the context for the design challenge, and outlines the criteria and constraints of the EDP. The letter challenges students to design and build a prototype of a stringed instrument that could be sold by the toy company. To inform the prototype design, students explored concepts related to sound including amplitude, pitch, and frequency of sound waves through various activities, and applied their understanding to design a stringed instrument. Following the design challenge, the unit transitions to light. The light component of the curriculum begins by comparing and contrasting sound and light waves, followed by a series of lessons on the ways that light is absorbed, reflected, and refracted. Table 4.3 overviews the unit, which is followed by a short summary of each lesson as written in the final curriculum.

Table 4.3. *Summary of Team Do-it-Yourself Stringed Instruments Curriculum by Lesson*

Engineering Design Challenge: Students must understand volume (amplitude), pitch, keep track of budget, and have an unique design (creative) in order to use the engineering design process to create prototypes of stringed instruments for the DIY Stringed-Instrument Company.				
Lesson 1	**Lesson 2**	**Lesson 3**	**Lesson 4**	**Lesson 5**
Engineering Design Challenge: Plan, Test, and Prototype (5 days)	Introduction To Physics of Sound (1 day)	Modeling How Sound Travels (1 day)	Amplitude and Pitch (2 days)	Standing Waves and Harmonics (1 day)
Lesson 6	**Lesson 7**	**Lesson 8**	**Lesson 9**	**Lesson 10**
Review (1 day)	Introduction To Physics of Light (1 day)	Reflection (1 day)	Refraction (1 day)	Absorption (1 day)
Lesson 11	**Lesson 12**	**Lesson 13**		

Science Writing: How Light Travels (1 day)	Comparing and Contrasting Sound and Light (1 day)	Redesign and Client Letter (2 days)

Lesson 1: Engineering Challenge: In the opening sequence of the DIY curriculum, the students receive a client letter from Do-It-Yourself Stringed Instruments requesting their help designing a stringed instrument that is functional, cost effective, and aesthetically appealing. The information students need to make their prototypes is included in the letter, as well as the list of materials they have available to them.

Lesson 2: Introduction: The Physics of Sound: Lesson 2 introduces students to the science of sound. It begins by engaging students in a whole class discussion using the Critical Response Protocol in which they engage in observing, discussing, questioning and speculating about a video where a 33 rpm LP vinyl record is playing. After the introductory discussion, they are shown a PowerPoint on the elements of physics (some new material, some review) and are instructed to think about upcoming activities that may help them better understand the science and technology involved in sound.

Lesson 3: Wave Models: This lesson uses the common children's toy, *Slinky,* as a model for illustrating sound and light waves. Waves will be defined loosely as "a series of pulses."

Lesson 4: Vibrations: Amplitude & Pitch [Bangs & Twangs]: This lesson is designed as a series of four stations with activities that illustrate how all sounds are a result of vibrations of particles through a medium.

Lesson 5: Standing Waves and harmonics: This lesson synthesizes the previous lessons. Students watch a series of videos that model how standing waves correspond to pitch. The videos help students understand the concept that waves have frequencies that make pitches we experience as sound.

Lesson 6: Review and Build: This lesson serves to transition from sound to light and serves as a review of what students learned in previous lessons about sound waves.

Lesson 7: What is Light?: In this lesson, students get a basic understanding of light by learn exploring the behavior of light as it travels through different mediums.

Lesson 8: Reflection: In this lesson, students learn that the angle of reflecting light onto a mirror will be reflected at the same angle. Students use protractors to measure this, and challenge themselves to try to get their light to hit a target point.

Lesson 9: Refraction: In this lesson, students explore refraction by trying to "spear" (spaghetti) a "fish" (penny) in water. Students observe refraction and learn that light bends when it travels through substances like water.

Lesson 10: Absorption: In this lesson, students explore how light is absorbed by looking at LEGOs through different color light filters.

Lesson 11: Concluding Light: In this lesson, teachers and students participate in a Shared Writing strategy to build a conclusion statement about the behavior of light. The lesson serves as a formative assessment to help the teacher determine what students learned about light, how light behaves, and identify any possible misconceptions.

Lesson 12: Sound and Light Compare and Contrast: In this lesson, students compare and contrast sound and light, and record their ideas in a Box-and-T Chart.

Lesson 13: Redesign/Client Letter: In this lesson, students compose a letter to DIY Toy Company sharing their stringed instrument prototypes, including the ways they believe they can make improvements to their prototypes.

The descriptions above summarize the integrated STEM curriculum. In the following, I provide more information about how each teacher described their implementation of the co-developed curriculum during the *Looking at Student Work* session, and share a small sample of the student work each teacher brought to the session. Finally, I conduct my analysis, identifying and articulating patterns within the data.

Analysis: Team DIY *Looking at Student Work* Sessions

My analysis is structured around a series of assertions and corresponding critical incidents (Patton, 2002) from the protocol-guided sessions. A critical incident is a report made by research participants, which I use to build a picture of the patterns of participation and how those patterns yield insights into how collaboration and refinement of the curriculum supports PDC development, as well as the role the protocol interventions play in affording and constraining the process. The critical incidents were selected because they are representative, illustrating how the teachers in this study drew upon personal and curricular resources to construct instructional activities and use what they learned from their decisions to offload, adapt or improvise the curriculum to inform the redesign of their curriculum.

Matthew's Looking at Student Work Session

In the first *Looking at Student Work* session, Matthew brought in six student-designed stringed musical instrument prototypes (see Figure 4.1) and a scoring rubric.

The prototypes were selected to represent a range of success levels, and the rubric provided assessment criteria with which to score the student work.

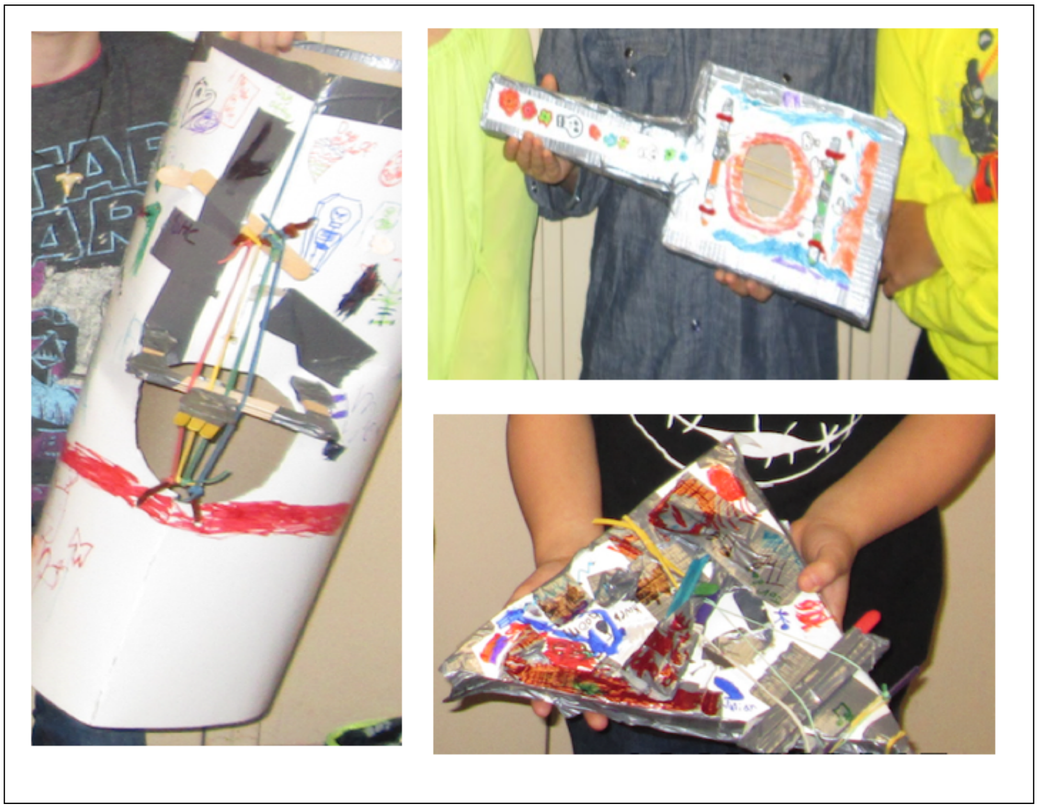


Figure 4.1. This figure shows students' work samples from Matthew's *Looking at Student Work* session.

How Matthew Described His Implementation

Following protocol guidelines, the session began with Matthew providing an overview for the assignment. Matthew highlighted how the team tied together grade-level standards for 3rd grade sound and 5th grade light with the engineering project. He briefly discussed grouping, the EDP criteria, materials, as well as classroom issues related to troubleshooting and unanticipated challenges that arose:

Well, Kathryn and I teach different grades so we've banded our science

> *curriculum . . . and then built an engineering project that tied those concepts together in a project that we could construct under a fictitious client to make a product. Third grade's focus is on sound and fifth grade is on light and we sort of put them together into a sound and light unit. We talked a lot about the different tools and materials . . . throughout it there would be natural stopping points where I thought, 'Oh, if I don't do some clear teaching on durability, this will be a disaster.' I started with troubleshooting what could be potential problems, also the flimsy cardboard could be a problem and duct tape sticking to it is always a problem. So we just kind of worked from there. I could go on and on but that's sort of the overview.*

In his introduction, Matthew foreshadows themes that would come up over-and-over again: tensions associated with creating an integrated STEM curriculum that encompassing both sound and light standards, meeting the developmental needs of both 3rd and 5th graders, how their original plan was "lofty" for 3rd graders, managing students and materials, and troubleshooting potential problems. While it is too early to draw final conclusions based on this, it is possible to posit that even in his introductory remarks he foreshadows several aspects of how curricular and personal resources interacted to influence his decision to make adaptations to the co-developed curriculum.

This excerpt also reflects several aspects of the teacher and curricular resources available to him. How he relied on his ability to conduct "mini-lessons" as instructional opportunities presented themselves, and how the problems he perceived instigated his decisions. For example, his tone hints at the prototyping process being a bit chaotic, and implies that his was out of alignment with his goals and beliefs about structure. Thus, it provides a fleeting glimpse into a misalignment between his desire for structure, which he imposes with “mini-lessons,” and the open-ended nature of the EDP.

Kathryn Protocol-Guided Session

Kathryn also brought in six student-designed stringed instruments and the same scoring rubric to her *Looking at Student Work* session (see figure 4.2).

Figure 4.2. This figure shows students' work samples from Kathryn's *Looking at Student Work* session.

How Kathryn Described Her Implementation

In describing her implementation, Kathryn highlighted the sequence the sequence of the EDP, and how she made connections between the curriculum and music by connecting to her students' and her husband's interests in playing musical instruments:

> *The engineering design process. So, we started off with the client letter, and then we had them create their instruments. Then I had three of my students talk about the violin, the viola and the cello. Then my husband came in and talked about the guitar and how the guitar worked. Then we redesigned so these are their redesigned pieces and then yeah, and we recorded and tested . . . I'm going to have them write a client letter, to the client and wrap it up that away. Presenting their instruments rather than just saying okay.*

In her introduction, Kathryn foreshadows ideas the team revisited several times. Her focus on the EDP illustrates some of the ways she and Matthew both drew upon the co-developed curriculum -- introducing the EDP with the client letter and prototyping. Following the EDP with relative fidelity, adapting with writing assignments when she recognized instructional opportunities to do so, and making connections to students' lives all reflect her instructional capacity, goals and beliefs about STEM curriculum. Her description also illustrates significant variations in the personal resources and the aspects of the curriculum they prioritized. For example, her emphasis on writing varied from Matthew's. Implicit in this summary is a reflection of the teacher and curricular resources she emphasized and had available to her.

With these descriptions in mind, I will now transition to the analysis, which is organized around assertions and supporting critical incidents. The analysis is organized around assertions and supporting critical incidents. First, I provide a short description of the context, followed by an assertion, and a critical incident -- an excerpt of data from the protocol-guided session that informs the assertion. Finally, I present my analysis using the DCE framework to articulate patterns of participation and PDC development.

Looking at Student Work Analysis

Six main assertions were drawn from the analysis of Team DIY's *Looking at Student Work* sessions. In the following analysis I present my assertions about how to interpret the data, supporting each with a critical incident. The critical incident, though taken from Team DIY's session, is not solely reflective of this team. Rather, the critical incident was selected because it is a "good" example of the ideas that surfaced during the discussions of all three cases.

Assertion 1

The use of a protocol for examining student work makes classroom practice visible.

Critical Incident 1

This critical incident is taken from the team's first *Looking at Student Work* session following Matthew's implementation, and supports Assertion 1. The critical incident took place as the team transitioned from Matthew's overview to having participants individually score student work with the rubric he had brought.

> ***KURT:*** *I just realized, we're going through with cost.*
>
> ***MATTHEW:*** *Yes, so part of the thing on cost...So Kathryn, when I was doing this, every time I had a little clipboard with all the teams and every time they got another foot of tape, I would write it down and that worked great for like three or four days. Then after a while, I was in the middle of troubleshooting and all kinds*

of other things, so I couldn't even keep up with this. They're like, '[I need] a bunch of tape,' I'm like, 'take one if you need it.'

KURT: *Yeah. But the kicker is that we gave them $50. The tape was a dollar and the cardboard was like a dollar and all they were using was tape. So, it was like unless they take 50 of these things, the tape, they're going to be under budget. So at some point, we also went, 'they're under budget.' They've had four of the [chuckles], they're under budget by $46.*

MATTHEW: *I think with 3rd graders it might have been a little lofty to expect them to really keep track of that, as opposed to, because you need everyone's hands.*

When Kurt, Team DIY's classroom coach, says, "I just realized, we're going through with cost," it cues Matthew to explain why he decided not to have students keep a budget, one of the stated criteria the student work was supposed to be scored by. Kurt's words are also a signal of growing awareness that it is impossible to score the student work given the fact that Matthew's students did not keep a budget for prototyping their instruments. As such, the protocol for *Looking at Student Work* provided the impetus for making Matthew's classroom practice visible to the group.

Rather than implement the curriculum as written and having the *students* keep track of costs associated with their prototypes, Matthew had devised a way for him to keep track of costs on behalf of students. When keeping track of scores became too much for him to manage, he dropped the budget altogether. This shows curricular and teacher resources interacted and were transformed as classroom events unfolded. The co-developed curriculum specifies that students keep track of costs associated with their prototypes to satisfy the mathematics integration requirements of STEM curriculum. As such, the curriculum initially served as the primary curricular resource to achieve SEM integration. SEM integration is aligned with the domain representation category of the DCE framework. When Matthew devised a strategy to meet SEM integration goals to help students keep track of costs, he was drawing upon his personal resources to adapt the original curriculum. Initially, then, the manner and degree to which he approached the modification was in alignment with the intent of the original curricular goals for the SEM domain representation.

When management of his modification became too much, he made a more significant adaptation, dropping the budget requirement. In the process, he disrupted the SEM integration goals, triggering the first of several discussions he and his team would have about the benefits and alternative to budget to achieve mathematics integration. At this point, we see evidence of dissonance between the goals of the intended curriculum SEM goals and what was possible in his classroom. This dissonance is the beginning of STEM PDC development. While there is no resolution yet, we already see small attempts to reconcile the problem. When Kurt mentions that everyone was under budget, it implies a suggestion that the budget was not effective any way. When Matthew suggests it may have been “lofty” to expect 3rd graders to keep a budget, he is indirectly justifying his decision. By making classroom practice visible, the ways in which the teachers offloaded, adapted or improvised the original curriculum became apparent. When the team gains awareness, it presents an opportunity to justify decisions, modify the co-developed curriculum, and a host of other options.

One of the tenets of protocols is that they segment boundaries of conversation, with the goal of facilitating professional conversations that help participants assess the efficacy of instruction and gain understanding of student learning (McDonald et al., 2014). One of the ways the *Looking at Student Work* protocol accomplishes these goals is by emphasizing the use of evidence, aligning rubric criteria with scoring decisions. Thus, the protocol establishes a framework for discussion that essentially required Matthew to share that he did not have the students keep a budget. In short, the protocol guidelines of requiring evidence for scoring decisions created the opportunity to discuss modifications to the curriculum, inviting incremental development of STEM PDC.

The following critical incident took place as the team transitioned from scoring the student work individually to sharing and discussing scoring decisions

Assertion 2

Facilitation strategies afford collaboration and refinement of curriculum.

Critical Incident 2

> ***ALEXA:*** *Are we ready to talk about this? . . . Let's just start with [prototype] A, for example, and then talk about it one at a time, like that, and see if we overlap or where we don't.*
>
> ***KURT:*** *So for A, I had two for volume. I had three for pitch. Three for creativity and four for cost.*

KATHRYN: *I had two for volume, two for pitch, three for creativity. I didn't do cost because, I don't remember.*

MATTHEW: *Yeah, I didn't do cost.*

ALEXA: *I didn't either.*

KURT: *I didn't do cost because I just assumed they all made it so I gave everybody a four.*

Rigid adherence to the *Looking at Student Work* protocol guidelines dictates use of evidence to support scoring decisions. In this excerpt, the only way to abide by the guideline for evidence is to not score the student work for budget criterion, which three members of the group did. However, Kurt, the team's coach, assigned fours to all student work samples because, "I just assumed they all made it." In cases where participants differ in their scoring decisions, the protocol guidelines direct the group to discuss the scores and cite evidence to justify them. In this case, exercising a flexible facilitation strategy, allowed the facilitator skipped this. This decision avoided an unproductive avenue of discussion and allowed the team to move on and remain focused on scoring student work. Since the team had already discussed the fact that students had not kept a budget, discussion about scoring discrepancies was not relevant to the broader purpose of the protocol intervention -- to use student work as a proxy for instructional effectiveness and, in doing so, guide the process of "educating ourselves" (McDonald et al., 2013).

One way protocols accomplish "educating ourselves" is through intentionally segmenting boundaries by placing artificial constraints on the conversation (McDonald, 2013). The goal of the protocol interventions in this study was to confront problematic aspects of the co-developed curriculum to improve instructional practices and inform curricular outcomes. In this instance, the facilitation move to delay discussion of scoring discrepancies avoided an obvious, and likely unproductive, discussion. Thus, flexible facilitation afforded collaboration and refinement by delaying judgment until the appropriate time -- reflection and next steps.

This event demarcates the early stages of the team's understanding of STEM curriculum related to SEM integration. Matthew raised the issue of budget with the team, and in doing so, problematized it by sharing that that component of the curricular resources the team had design did not work for him as intended. At this point, there is not a solution, but in the series of critical incidents that follow, the TDT explores the problem more and elucidates how problematizing of budget led to development of STEM PDC as the team grappled with the issue.

The following critical incident took place as the team transitioned from scoring student work to reflecting upon what they had learned and discussing next steps.

Assertion 3

Making classroom practice visible surfaces problems with the curriculum, solutions to it, and opportunities for improvement.

Critical Incident 3

> ***ALEXA:*** *How about the cost thing? Like, it was impossible to assess cost on these we just did.*
>
> ***MATTHEW:*** *Right.*

KURT: *Yeah. It was impossible to assess cost the way we were doing it in the room, too.*

ALEXA: *Were they doing the math?*

MATTHEW: *They started it, and I started it. After a while, it's like--*

KURT: *Yeah, and then I gave up.*

MATTHEW: *Yeah, right. You just kind of give up.*

ALEXA: *So, why did you put cost there to begin with?*

MATTHEW: *Because it was part of the whole idea of working for a client and you're supposed to have math involved in it . . . and the hard part is it's hard to really get math involved in this, in any genuine way.*

KURT: *Cost-efficient. Seeing something that every engineer takes into account. But yeah, you could easily drop it. It doesn't need to be there.*

MATTHEW: *And the hard part is, it's hard to really get math involved in this in any genuine way.*

In this excerpt, the problem of budget is once again the topic of discussion. This segment further illuminates the nature of the problem with the budget criteria, why the team selected it in the first place, and how Matthew's goals and beliefs about budget interacted with the SEM integration goals of the curriculum to drive his decision to omit budget. These insights illuminate how STEM PDC developed as the interactions of curricular resources drawn upon (co-developed curriculum, informed by *EngrTEAMS)*, interacted with teacher resources in an effort to address the problem when the co-developed curriculum did not work as intended.

The problem. Earlier Matthew had revealed that he thought having 3rd graders keep a budget was “lofty,” reflecting the Goals and Beliefs category of the teacher resource section of the DCE framework. To address his concerns, he devised a strategy that preserved the curricular goals of mathematics integration by creating a budget tracking systems that he managed. When this did not work, he let go of the curricular goal of integration.

Co-constructing and problem. In this segment, Matthew and Kurt co-construct a more complete picture of the nature of the problem. Matthew and Kurt speak to the challenge of keeping track of the budget by eliciting the classroom, “It was impossible to assess cost the way we were doing in the room too” (Kurt), and how it led to just giving up after the initial attempt to adapt the process by which budget information was collected on behalf of students. Their depiction is one of a collaborative effort, even though Matthew, not Kurt was ultimately responsible for curricular decisions. For example, when Kurt says, “Yeah, and then I gave up,” he is positioning himself within the conversation as if he were the teacher. While I am not going to analyze this process of co-constructing fully, I do want to point it out because it foreshadows a topic that will become important later: sharing classroom experiences in order to shed light on the conversation at hand.

This segment also reveals an incremental, rather than direct, process of drawing upon curricular and teacher resources to address the problem of practice budget presents. An incremental process of drawing upon resources to address instructional opportunities that arise in the classroom implies a strategy of using what resulted from the initial efforts to inform the next steps. The "steps" inform an understanding of STEM PDC development, which can be summarized as follows:

Step 1: When faced with a mismatch between intended curriculum (students keep budget) and enacted curriculum (lofty for 3rd graders), draw upon available teacher resources to adapt *how* budget information is collected (teacher, not students, manage).

Step 2: Use outcomes to determine next steps. If initial effort works, then process by which budget is collected differs from the intended curriculum, but budget goals of the curriculum are fulfilled. If initial effort does not work, then either enlist other teacher resources to solve problem, or omit intended curricular goals.

In Step 2, both options are adaptations, but come with very different implications for redesign of the curriculum. The outcome of instructional choice, in this case, was adapting the original curriculum by omitting budget. Matthew and Kurt hint at the reasons behind the decision to omit budget rather than try something else -- "it doesn't need to be there." There is a tension between the goals of the curriculum (and the spirit of integrated STEM curriculum), and the classroom "won."

This excerpt demarcates the beginning of the process of development of STEM PDC for the team. Despite the connection of the budget to the co-developed curriculum, the teachers were not completely satisfied with the decision to use budget as the way to integrate mathematics. Making classroom practice visible surfaced and enhanced the team's STEM pedagogical design capacity as they co-constructed a more complete picture and, in the process, reveal how curricular and teacher resources were used incrementally to address problems of practice. Critical Incident 4 provides further support for Assertion 2.

Assertion 4

Storytelling mediates development of STEM PDC.

Critical Incident 4

ALEXA: *So, how could you connect math?*

MATTHEW: *Well, they know what amplitude is now. The other experiments in our lesson have been great for that. They've seen the decibel meters and they've seen hertz on my apps, and how that is measured . . . You can only go so far in teaching an eight-year-old what that actually means . . . We can certainly talk about area, perimeter, volume, and different pieces of this, circumference. Which would be brand new for 3rd grade as well.*

KATHRYN: *And the 5th grade, that's a standard [unintelligible].*

MATTHEW: *Yeah, exactly. There are ways, but then where do I do it? Am I doing this just so that I can say I did some math? And is it actually feasible to do?*

KURT: *Necessary.*

MATTHEW: *Yeah, necessary for this event.*

ALEXA: *So, math is probably not necessary.*

KURT: *It's absolutely not necessary. No, you can do the whole thing without any math. I think that having them draw the pictures and put what they thought their measurements were going to be on it was really smart and that's really good math. It was very eye-opening for the kids. I wasn't kidding. Many of them had* *instruments three inches, two inches and when we went, 'You know, that's like this.' [indicating 2 inches with fingers] That's good math. But is that happening every single day? No. And I don't think that takes away from the project. I'd still think it was good.*

MATTHEW: *When we were just starting, we began building this, and at the beginning the multiplication, the math was needed. It is possible, 'So this is what you drew. If you want to make it this long, you'll want to make it actually 12 multiplied by four.'*

In this critical incident, the conversation shifts from articulating the problem of budget to considering possible solutions. In doing so, they share stories from the classroom to inform their understanding. To address the question of how to integrate mathematics, the teachers draw upon their personal and collective resources to inform their ideas about what it means to "genuinely" integrate mathematics into the EDP.

Though, "you can only go so far in teaching an eight-year" old about the science of sound, In his evaluation of the available curricular resources within the co-developed curriculum, Matthew determined the science lessons had been effective for student understand of the science of sound. His suggestion that a viable alternative to budget might be measurement (perimeter, volume, circumference) gets the attention of the team. It is a 5th grade standard (Kate), it is "really smart" and "really good math" (Kurt), and "it is possible to do" (Matthew). As the team begins to consider viable alternatives to budget they enlist the classroom to inform the decision through storytelling.

Storytelling is a term I use to refer to bring classroom events to bear on the conversation. This is a strategy where the teachers and their coach present the classroom experiences as evidence or justification for ideas presented during the protocol-guided session. In this case, Kurt shares classroom events to provide support for the idea of substituting budget with measure to satisfy the mathematics integration goals.

Storytelling served as a mediating factor to inform the TDT's evolving understanding of how to productively and genuinely integrate mathematics and, doing so in a way that was perceived to be doable for both students and the teacher. As such, this segment provides evidence of how the team's PDC shifted away from simply replicating what they had learned during the summer PD. Storytelling invited participation by the whole group. Sharing individual insights does not refute other ideas, but builds upon them. PDC relates to a teacher's ability to perceive and mobilize resources for curriculum use (Brown, 2002; Brown & Edelson, 2003), but it is also about transforming resources (Brown, 2002). As the TDTs shared ideas they co-constructed their understanding and transforming the repertoire of resources available to them for mathematics integration.

Assertion 5

Variations in teacher's goals, beliefs and experiences influenced their decisions about curriculum use and redesign.

Critical Incident 5

> ***MATTHEW:*** *To me the most genuine math, if you think of math as measurement, was measuring hertz for the pitches, and the decibels . . . even if you did like a bang, the decibel meter goes off the chart . . . It's difficult to record decibels because they don't hear that as noise, but you can actually measure it. It's about*

55.

KATHRYN: *Yeah. When we added it [budget], I was thinking of the Oil Spills [Engineering is Elementary kit], because I do think that it does have a purpose to it, because they do need to know how to make a cost efficient thing [prototype] if they're wanting to sell it to business. It needs to be cost efficient. You could, [make it] what it is supposed to be. Like, one cotton ball; they're spending like a billion dollars on that cotton ball because in that instance, because that real life situation is actually a product. Like that is that much money. So I think it does give them an ability to see like, 'Oh, this is real.' So like, if there is a way to think of rubber bands and then compare it to the guitar strings my husband buys for his guitars, and somehow put it so it's at that price. It makes more sense realistically. But I don't know. I like the cost piece, especially for 5th grade, because they need to know how to estimate and be like, 'Okay, well I spent this much money already,' and they need to realize that they have to keep track of it. That's part of their curriculum.*

MATTHEW: *I like the activity in general, but it was a LOT of running around and rescuing projects and then, holy cow it's time to clean up, and now I have to put all of these someplace.*

Up to this point, the TDT has floated three alternatives to budget: nets, calculating perimeter and volume of prototypes, and measurement of sound waves. In this excerpt, the team begins to analyze the alternatives in relation to their original idea of using budget. Kathryn, who has been relatively silent to this point, proposes an alternative to what the team had considered up to this point. Rather than replacing budget, she suggests a way to make the budget more authentic by aligning the prototyping materials with "real-world" materials and their cost.

These different approaches to integration are a reflection of their differing goals and beliefs about the value of budget as an integration strategy for the curriculum. The team realized mathematics was "absolutely not necessary" (Kurt) for students to use as originally written into the curriculum, however, they had differing goals and beliefs that influenced their ideas about the revisions. Their differing goals were partly driven by their classroom experiences. Matthew's classroom experience with the budget criteria included "a LOT of running around and rescuing projects," which he was not comfortable with. Kathryn liked the budget criteria, "especially for 5th grade," because she believed that the problem was not so much 3rd graders not being developmentally capable of keeping a budget, so much as the problem resided in the inauthenticity. Perhaps helping students see the value in keeping a budget would result in better outcomes. Her previous experiences teaching the Engineering is Elementary Oil Spill kit, influenced her belief that it was manageable in the classroom. She also believed the budget served an important educational purpose for students because students "need to know how to make a cost efficient thing if they're wanting to sell it to business."

At this point the teachers and their coach had raised several issues related to the budget criteria as written in their curriculum and, in the process, shifted their thinking about integration of mathematics beyond what they had learned during the summer PD. While they had different goals, beliefs, and experiences they were drawing upon to inform their thinking about redesign, these resources were morphing, expanding and being elaborated upon as new ideas were considered. For example, the idea of budget, originally a curricular resource from the co-developed curriculum and summer PD, was changing due to new ideas. The idea of budget as a "cost-efficient" option, taking new form. Budget as a resource was not being floated as more genuine -- it is what engineers do and, if "real-world" materials used to make stringed instruments could be aligned with the prototyping materials, budget as a curricular resource is transformed into a more genuine option to draw upon and inform design decisions. In the following assertion and critical incident, I return to the topic of "nets" for a more complete analysis.

Assertion 6

Customizing the co-developed curriculum through improvisations in the classroom, refines understanding of STEM curriculum.

Critical Incident 6

Critical Incident 6 took place during Kathryn's post-implementation session and picked up on a suggestion Matthew made during the previous *Looking at Student Work* session when he said, "We can certainly talk about area and perimeter and volume and different pieces and different panels of this circumference, which would be brand new for their grade as well."

> ***ALEXA:*** *So, I forgot. I went off my protocol, and I totally forgot we didn't do the part about what do kids need to know and be able to do. So, I don't know at this point if we want to return to that or, I think it would be an interesting conversation, and talk a little bit about like feedback now that you've been*

through the process and scored this.

KATHRYN: *I can give one insight, which would tie into to what students need to know. So, right before we did this we did our Geometry unit, which focused on "nets" and 'what does this object or this 3D figure look like when it's flat?' My kids [got it] right away. I think, if I didn't teach nets before, because that group (pointing to student work) were talking about nets. They were like, 'okay I know that a rectangular prism needs this, this, and this.' I did ask them, I was like, 'if we didn't just learn Geometry, would you be able to do this?' they were like, 'No, I never knew what a net was.' So, I think that it was helpful that [the design challenge] was right after our Geometry unit focused on 3D solids . . .*

KURT: *Triangular and prism group was the same way. They were really quickly going.*

MATTHEW: *When I was working on this with my third graders, I kind of let them try and fail a little bit and then, or if someone was starting to approach an idea, we just stopped. Kind of like Workshop Model, "Oh this is what I just noticed somebody doing," and then did mini-lessons on what a net is. After, the kids actually started making one and so, eventually other kids got it.*

ALEXA: *So, are you saying that's in the Know or Do (referring to rubric prompt) category, or how would you implement that?*

MATTHEW: *Well, it's difficult because we have 3rd grade and 5th grade, so I struggle. Sometimes I'm just in a frenzy. How do I keep this more inquiry without giving too much ahead of time, but they are two years younger, and it shows. And* *so I had to be careful with not letting their frustration to get into complete meltdown. So, I would say that if I were to backup now, I would look at this kind of stuff and say, 'what's going to happen when you pull this string, held together on tape? Overtime it's sliding out. Eleven kinds of different little lessons I would do first maybe. So, maybe even mini-lessons, not only design challenges, but really testing ways to make a component of it. So, how you could build a bridge? How you could anchor a rubber band? How you can manage tape? There is an endless list.*

In this critical incident, Matthew and Kathryn were responding to Alexa's prompt, to identify what students need to know and be able to do for success. The prompt triggered a conversation that helped the teachers realize they had both improvised around the same topic, the geometry of nets. A net is the mathematical term used to describe the transformation of geometric shapes from 2-D to 3-D form. This illustrates how teachers drew upon their subject matter of mathematics (teacher resource) to customize the co-developed curriculum through classroom improvisations. Specifically, the teacher resources available to them related to nets interacted with the curricular resources specific to domain representation.

Both teachers, by explicitly teaching how to transform 2-D into 3-D representations (and vis-a-versa) recognized and took advantage of an unplanned instructional opportunity to authentically apply mathematics knowledge to the engineering design. Both teachers also felt it was helpful for student learning. Kathryn recognized the benefits after the fact, and her students confirmed her observations.

Matthew recognized an instructional opportunity in response to his students, which he reported helped them move forward in the project. Throughout the implementation process, Kathryn and Matthew exhibited differing patterns of implementation, Kathryn tended to offload the curriculum and Matthew tended to adapt. However, both did improvise, as this case indicates.

This instance exhibits how their improvisation strategy for crafting instructional design were constructive for their implementation and for developing their understanding of STEM curriculum and its outcomes for students. There is evidence that their goals and beliefs about the co-developed curriculum influenced these decisions. Kathryn had taught STEM curriculum before and brought those experiences to the co-developed curriculum, and she perceived the co-developed curriculum working for her students in most cases. Matthew tended to rely on his ability to read his students and respond to their needs during implementation. There is some evidence that he drew upon his familiarity with Reader's Workshop to craft mini-lessons as the need arose. Furthermore, this seemed to work for him, as evidenced by his response that, if he were to back-up and do this again, he would plan for mini-lessons.

This incident also illustrates the role the protocol prompt for what students need to know and do mediates collaboration and refinement of the curricular ideas, which supports development of STEM PDC. The prompt triggered Kathryn to make visible an improvisation she had not previously mentioned. It also surfaced that Matthew had also integrated nets into the EDP, something he also had not previously shared during the *Looking at Student Work* sessions. While, Kathryn and Matthew's strategies differed --

sequencing the geometry up-front of the challenge in the case of Kathryn, and an on-the-fly "mini-lesson on what a net is" in the case of Matthew -- both drew upon their experience teaching geometry and Matthew's prior experience using the Workshop Model to inform their instruction. The team ultimately changed the procedures (Task Representation) and included explicit instruction on nets, which makes the process of transforming 2D cardboard into 3D stringed instrument (Domain Representation) explicit to students and support mathematics integration. In doing so, they drew upon their personal resources and curricular resources, which interact to influence curriculum use (improvisation). The discussion and curricular modifications demonstrates how new knowledge of STEM curriculum developed, and this is a reflection of development of STEM PDC. The teachers honed their STEM PDC related to the integration of mathematics into the engineering design challenge.

My purpose in analyzing the *Looking at Student Work* sessions was to demonstrate how curricular features and the protocol-guided discussion combine to reveal how PDC develops offloading, adapting and improvising, show how variations in implementation of the co-developed curriculum are due to teachers capacity to recognize opportunities for improvement and respond to those opportunities by drawing upon their personal resources, and how current curricular and teacher resources interact and are transformed as teachers bring their problems and solutions to the team. Throughout the *Looking at Student Work* session team DIY exhibited curriculum use that reflected a range of strategies for offloading, adapting and improvising their original curriculum. The teacher also demonstrated a range of personal resources they relied upon. Those resources interacted with the curricular resources from the curriculum and what they had learned during the summer PD about STEM curriculum to craft instruction for their students. The teachers shared their curricular modifications with the team and, in doing so, their ideas about STEM curriculum were discussed and refined. Sometimes these discussions led them to redesign the curriculum. Other times, the TDT made the decision to stay with their original ideas. In either case, their ideas and the resources they had available to them were transformed as they gained new insights and co-constructed their evolving understanding. In the following section, I build upon this by analyzing the *Thinking Through a Task* protocol-guided session.

Team DIY *Thinking Through a Task* Critical Incident Analysis

The *Thinking Through a Task* protocol-guided session took place after all team members had implemented the curriculum and participated in the *Looking at Student Work* sessions. The purpose of the *Thinking Through a Task* protocol is to support collaborative design (or redesign) of curriculum or curricular tools.

This excerpt took place late in the protocol-guided session as the team began the reflection part of the protocol, when Kathryn brings up a point that had been discussed previously.

Assertion 7

Facilitation creates opportunities to shift teachers' thinking about curriculum for their classroom towards curriculum for others, and serves as a resources for PDC development.

Critical Incident 7

KATHRYN: *That first question, that was the last question I ended up filling out because I was like, 'how will you model it?' I was like, 'well you use it!' It's just hard to write down how to model it.*

MATTHEW & KURT: *Yup (nodding in agreement).*

KATHRYN: *You're like, that's kind of challenging to do.*

ALEXA: *Well we sure can talk about it if you want. I'm thinking in particular of something Matthew said a long time ago, after you first implemented. You talked about having the kids model with their bodies. Do you remember that?*

MATTHEW: *Let me think.*

ALEXA: *You had them be the waves or something.*

MATTHEW: *Oh, oh, right. I think what we did, we both did that in our lesson too. We did like a stadium wave and pulses (teachers begin to gesture, moving their arms with a wave-like motion and opening and closing hands).*

ALEXA: *What's this (mimics hand opening and closing gesture)?*

KURT: *Pulses. You send a pulse. You have everyone hold hands and then you send a pulse around the circle.*

ALEXA: *To me that's a way of modeling it too.*

This excerpt reflects how the protocol created an opportunity to shift the team's thinking about how to model academic language, and build what Huizinga, et al. (2014) refer to as *design expertise*. Kathryn is essentially bringing a "problem" to the team, the problem being her uncertainty about what it means to model academic language. Earlier the team had already discussed how to model academic language, and the team still lacked clarity. For example, consider how Kathryn and Matthew had "answered" the prompt:

> ***KATHRYN:*** *I really had to think about this section. So you guys will probably add a lot to it. Um, how will you model use of academic language skills in content for students? Um, I kind of put it into the discussing with each group. Since we kind of started it off with the engineering design process and went back to it at the end, I said, through the different lessons after the initial design process that modeling, coming to it almost afterwards.*
>
> ***MATTHEW:*** *I had something very similar to what you had Kathryn. I wrote regular modelling of the use of content-specific terms throughout the lessons and with each groups . . .*

These responses are vague, and from the perspective of a curriculum designer, do not provide instructions to any future curriculum user on how to introduce, teach or assess academic language. In both of these segments, Kathryn is essentially making a bid for help for the team to help her clarify how to model use of academic language. What is striking about this section, especially because the team had already responded to the prompt, is that the team clearly had provided in-process supports for students related to academic language when they had students physically embody how sound waves travel. The "problem" is one of making the transition from what they do in their own classroom and how to design a curriculum for use by other teachers. In their original curriculum, they had treated attention to academic language as a list of key vocabulary terms and definitions.

The *Thinking Through a Task* protocol was designed to think about curriculum holistically. Curriculum design expertise requires a range of relevant knowledge and skills beyond pedagogical and subject matter knowledge including curriculum consistency expertise and related curriculum design skills such as systematic curriculum design skills, formative and summative evaluation skills, and curricular decisions-making skills among others (Huizinga et al., 2014). The protocol created an opportunity to shift the team's thinking about how to model academic language by creating dissonance that forced them to think more deeply than a list of vocabulary terms.

The DCE framework describes three aspects of curricular resources -- representations of content, procedures and the physical nature of the curriculum materials. Things like materials lists, learning objectives, and how to introduce and teach academic language are core aspects of any coherent curriculum that other teachers will use, and are aligned with Physical Objects component of the framework. Thus, the protocol created an opportunity to think about academic language in their curriculum more broadly and reflects how the team was drawing upon the curricular resources and personal resources, resulting in PDC development related to the physical nature of the curriculum.

In this case, the team did not recognize what they wrote into their curriculum as modeling academic language, and it was necessary for the facilitator to draw their attention to it and help them name it. If a teacher is going to be using a curriculum they designed, it may not be necessary to explicitly writing down how to introduce and teach the vocabulary terms. However, in writing curriculum for others, it becomes necessary to articulate more than a list of vocabulary terms with a dictionary definition. When Alexa referred to an example one of the team members had talked about in a previous *Looking at Student Work* session, it served to link classroom practice with the practice of writing curriculum other teachers could use. It also transformed the resources available to the teachers, shifting the curricular resources from a list of vocabulary terms and definitions for each lesson plan within the unit into thinking about vocabulary development in an entirely new way. The protocol, asked about "in-process supports" for students. In placing something the teachers were familiar (academic vocabulary) within an entirely new context (modeling academic language), caused the team to hesitate and to rethink their ideas.

Shifting their perspective between their classroom practices and curriculum design was a "problem" all of the TDTs had in their respective processes of co-developing their STEM curriculum. Their classrooms, combined with the curriculum itself served as important resources the teams drew upon and often helped them make important and productive adaptations and improvisations to the curriculum. At the same time, they often struggled to articulate clearly and with curricular coherence *how* they did what they did and translate that into the curriculum in a manner others could use. None of the teams would ever simply have students copy vocabulary words and their definitions and consider themselves done teaching the academic language necessary for their unit; yet, that is how it was originally written into the curriculum. The *Thinking Through a Task* protocol and its reliance on an outside facilitator helped the team shift their thinking toward greater specificity and bring their ideas in closer alignment with thinking about curriculum for others.

Assertion 8

The protocol surfaces different goals and values for assessment practices in their own classroom for assessment than they do for the co-developed curriculum.

Critical Incident 8

In this excerpt, the teachers are sharing their individual suggestions for things that they feel require modification in the curriculum.

> ***KATHRYN:*** *Well, I just put rubric because that's one thing that I think we both want to change. And also the area that I thought about was modeling [academic language]. So I was like, fix different parts of the modeling. Because I think there's just little things that we need to revamp. I know at least in my part I wanted to revamp. Plus, the videos we used. we said CRP [critical response protocol] while we were talking. So I just added that.*
>
> ***MATTHEW:*** *Another modification that will come through with our writing today, there are certain little adjustments you make because we banded as 3 and 5, and like Kurt was saying, Kathryn's kids could just go, 'Oh, I know exactly what to do and not do' as you start this. My kids still had to do quite a bit of trial and error because they are two years younger.*
>
> ***KURT:*** *. . . we have to remember to take cost off the client letter because none of us liked the prices and if this is used, like 5 years from now all those prices will be different anyway. So, we should let teachers establish those costs on their own.*

And I also put the rubric down. We need to change how we measure music volume. I liked the, 'can you hear from this far away? Can you hear it from this far away?' That's something they can test.

Matthew: Umm hmm, yup.

KURT: *They can test that on their own. They don't need us, you know, standing there with a device that is going to be hard to read anyway. And then, the bangs and twangs. We need to make it stations-based.*

Alexa: What? Say more about that.

In this excerpt the teacher design team was discussing final revisions of the DIY Stringed Instrument curriculum. They shared modifications that had come up in their *Looking at Student Work* sessions such as, changing the rubric, a better way to measure pitch and amplitude, and differentiating for 3rd and 5th grades. They also suggested modifications that had not come up previously. They have identified the changes they want to make and discussed some of the reasons for those decisions. In this we see they have relied upon their understanding of integrated STEM curriculum, combined with the protocol-guided evaluation of student work to identify adaptations to the curriculum's assessment. However, they never made the discussed changes to the assessment criteria. Thus, the protocol surfaces the different goals and values for assessment practices in their own classroom for assessment than they do for the co-developed curriculum.

Comparison of Team DIY Looking at Student Work and Thinking Through a Task

Analysis of the critical incidents related to the use of protocols for examining student work and redesigning curriculum provided several insights into the ways in which the protocol interventions afforded and constrained redesign of the curriculum. The *Looking as Student Work* protocol afforded collaboration and redesign of the co-developed curriculum in several ways as shown through the following assertions: (i) by making classroom practice visible; (ii) through flexible facilitation strategies; (iii) by surfacing problems with the curriculum, and curricular and teacher resources drawn upon to respond to problems; and (iv) by providing opportunities for storytelling that served as a mediating factor for understanding STEM curriculum. In addition, The *Thinking Through a Task* protocol afforded and constrained collaboration and redesign of the co-developed curriculum in two ways. It afforded collaboration and redesign by shifting teachers' thinking about curriculum for their classroom towards curriculum for others. It constrained collaboration and refinement due to variations in teacher's goals and expectations for the STEM curriculum.

The analysis also revealed insights into the personal and curricular resources the collaborative teams of teachers drew upon while examining student work and redesigning curriculum through the following assertions: (i) variations in teacher's goals, beliefs and experiences influenced their decisions about curriculum use and redesign; (ii) customizing the co-developed curriculum through improvisations in the classroom, refines understanding of STEM curriculum; (iii) variations in teacher's goals and expectations constrain collaboration and refinement of the co-developed curriculum.

Team DIY's offloads, adaptations and improvisations differed by team member, and those variations in use and in expectations within the team became visible during the protocol-guided sessions. Specifically, Kathryn's offloading of the EDP and SEM integration, contrasted with Matthew's adaptations (omitting budget and multiple iterations of prototypes) and improvisations (mini-lessons for math in the form of geometry of nets and EDP for prototyping). The original curriculum conceived of procedures that sequenced the prototyping in such a way that the first iteration was not informed by content, providing an opportunity for prior knowledge assessment for the teacher and providing a foundational common learning experience for students. In addition to the EDP sequencing, the original lesson plan called for students to apply science and mathematics to the engineering in an integrated manner. The differences in curriculum use created opportunities for deepened understanding of STEM curriculum when the teachers shared, evaluated, debated and redesigned the curriculum during the protocol-guided sessions.

In Kathryn's case, curriculum use provided opportunities for the team to see how the curriculum worked as written. In Matthew's case, curriculum use provided opportunities for the team to understand problems younger students and their teachers might face with the curriculum as written. It also provided opportunities to understand the role students play in driving decisions to offload, adapt or improvise, and the ways Matthew addressed problems that arose. By drawing on his understanding of the *Workshop Model* and associated pedagogical approaches, he crafted mini-lessons to address the problems. In both cases, the teachers read their students' needs to inform decisions to offload, adapt or improvise the co-developed curriculum -- drawing on the co-developed curriculum as a resource initially, and tapping into their own personal resources as the need arose to craft new instructional strategies. Furthermore, all of these instances served as resources to inform the curriculum redesign, and over the course of cycles of curriculum design, protocol-guided discussions, and evaluation of classroom artifacts, they built their repertoire of curricular and personal resources to inform their understanding of STEM curriculum. Even in instances of offloading, the personal and curricular resources the teams drew upon during the collaborative conversations expanded their understanding as the teachers shared their experiences. For example, Kathryn's explanation of how she drew upon her knowledge of the Engineering is Elementary (EiE) kits added to their understanding as they discussed possible aspects of EiE that could be borrowed from. The offloads, adaptations and improvisations reflect variations in use, and despite the emphasis here on variations in use, there were larger components of the co-developed curriculum that worked for both teachers as intended. The protocol-guided conversations were important tools for uncovering both similarity and differences in implementation, problems and successes of the intended STEM curriculum, and supporting the teachers' capacity to write curriculum for others.

Narrative Description of Case 2

In this section I provide a narrative description for Team PbRE's curriculum, followed by an in-depth analysis of their examination of student work sessions and curriculum redesign. First, I describe the team co-developed curriculum. Second, I describe how the implementing teacher described their implementation, followed by analysis of session. Third, I provide an analysis of the team's *Thinking Through a Task* protocol-guided curriculum redesign session. Finally, I provide a summary of the findings across both protocol-guided sessions.

Team PbRE Co-Developed Curriculum: Earth Science--Natural Resources

As previously mentioned, participation in *EngrTEAMS* meant the team agreed to: (i) Participate in a two-week professional development; (ii) Develop an engineering unit based on MN Science and Engineering Standards; (iii) Have each team member implement the co-developed curriculum with their students during the school year; (iv) Have each teacher participant meet monthly with a graduate student coach to refine the curriculum unit and submit it to be published in print and/or online by the end of the school year. Team PbRE was unique in that they co-taught their unit.

In this 7-lesson unit the participant teachers designed for 4th and 5th grade students in a STEM class, the students have been “hired” by a Medtronic-University partnership and asked to design an efficient way to power a mobile hospital using resources naturally available in Northern Minnesota. The context for client letter and corresponding design challenge was in response to a shortage of emergency medical units in Northern Minnesota, Medtronics and a University in the Midwest had teamed up to evaluate the best methods for powering a mobile hospital. Students will determine the best type of renewable energy resource to power a mobile hospital capable of serving rural areas of the state. Over the course of the unit students engaged in the EDP, and explored renewable, non-renewable, and recyclable resources, analyzed maps, conducted experiments to measure renewable energy output for solar, water and wind energy, and used their understanding to design a wind turbine that could be used to power a mobile hospital. Table 4.4 provides an overviews the unit, which is followed by a short summary of each lesson as originally written in the curriculum.

Table 4.4. *Summary Description of Team Powered by Renewable Energy's Curriculum*

Engineering Design Challenge: Students must understand the distinction between renewable, non-renewable and recyclable, and be able to conduct test for water, solar and wind energy in order to use the engineering design process to create prototypes of mobile hospitals for rural Minnesota to use in medical emergencies.				
Lesson 1	**Lesson 2**	**Lesson 3**	**Lessons 4**	**Lesson 5**
Introduction to the Engineering Design Process (1 day)	Introduction to Problem Scoping (1 day)	Introduction to Renewable, Non-Renewable and Recyclable Resources (1 day)	Engineering Design Challenge: Plan and Test Energy of Solar, Water and Wind (1 day)	Mapping the Terrain: Solar, Water and Wind Maps (1 day)
Lesson 6	**Lesson 7**			
Connecting Math: Analyze Data to Determine Most Energy (1 day)	Engineering Design Challenge: Re-prototype (1 day)			

Lesson 1 Summary: Students will be doing an engineering challenge by designing a track for a hex-bug. Students focus on their individual roles within their team contributions and efforts and the team's performance as a whole. Students learn the process of engineering thinking and will be introduced to concepts and vocabulary related to problem identification; constraints/limitations from the "client"; and product specifications/criteria necessary to complete the challenge.

Lesson 2 Summary: Just like real engineers, students will examine a Client Letter and identify "who needs what because why?" Students use the letter to generate a list of questions that they will need to answer in order to meet the client's needs.

Lesson 3 Summary: Students do a card sort organizing recyclable, renewable and nonrenewable resources to introduce them to terms and definitions, then have students relate the concepts to a series of images representing each category of natural resources.

Lesson 4 Summary: Students work in groups to measure the electrical output of three types of renewable energy available in Minnesota: solar, water and wind power. Using energy readers, students record the amount of energy produced, find the average of multiple readings, and draw conclusions as to the best type of energy to power the mobile hospital.

Lesson 5 Summary: Students use maps to compare the electrical energy output of solar, wind and water energy in Minnesota. They use their map analyses to determine which renewable energy should power the mobile hospital.

Lesson 6 Summary: Students work individually and in groups to design and prototype a wind turbine blade that will produce the most energy. Groups test the blade designs and select the one that will produce the most energy.

Lesson 7 Summary: Students test three variables: blade pitch, shape and, changing one variable at a time they isolate how each revision is affecting the energy output of their design.

The following section provides a narrative description of Team PbRE, an overview of the team describing their implementation, the *Looking at Student Work* sessions, followed by analysis. In the following I explore the Teacher-Curriculum Relationship (Brown, 2003) of Team PbRE's curriculum unit by briefly describing each lesson within it, and how the team describes their curriculum.

Context for PbRE *Looking at Student Work* Session

This team differs from the other two teams in that they co-teach the STEM course that the integrated STEM curriculum was implemented in. The team also differs from the other teams in that I am their coach, as such, at times I take a more active role in making suggestions during the processes of examining student work and redesigning the curriculum. Nonetheless, my role is still facilitative.

In the following section I will build upon my discussion of the teachers' classroom practices by delving deeper into the ways in which Team PbRE developed their STEM PDC during the *Looking at Student Work* sessions.

Analysis: Team PbRE *Looking at Student Work* Sessions

In the following, I describe the unique nature of the Team's *Looking at Student Work* sessions, introduce the Looking at Student Work session with a description of how they described their implementation, then build upon my discussion of how the team drew upon their personal and curricular resources to offloaded, adapted and improvised the co-developed curriculum.

Team PbRE is unique in that they co-taught their curriculum. As such, rather than having each teacher implement, followed by the examination of student work, this team met three times following implementation in different classrooms. Since the team taught the same curriculum to five fifth grade classrooms, it allowed them to mimic what the other teams did -- implement, bring in student work to evaluate and discuss, followed by implementation in their next classroom. Thus, the protocol guidelines were maintained, following an iterative cycle of implementation, discussion and reflection, revisions to curricular tools, followed by reimplementation.

How Team PbRE Described their December Implementation

At the first *Looking at Student Work* session, the team brought three students' science notebooks (SNBs), which they used to describe how they had implemented their curriculum. Science notebooks are a common strategy for enhancing student learning by more authentically modelling how scientists and engineers work, as well as promoting scientific literacy through embedding writing across the curriculum (Chesbro, 2006), and were a tool central to Team PbRE's classroom practices.

Following protocol guidelines, the session began with the team providing an overview of the assignment. Team PbRE emphasized how they sequenced their lesson, highlighting the role the client letter played:

> *So we started off with, 'who needs what, because why.' Then after they came up with who needs what because why in their groups, when we did our client letter they also wrote down other questions that they would have in order to answer that question. Then, the next part, we did a card sort activity (turning to card sort page in each notebook) with renewable, nonrenewable and recyclable. So they did it on their own first, and there was a lot of questions about things like paper and, what's the other tricky one? . . . Then we came back together as a class and we sorted them out together and we talked about why things might be.*

As the team introduced their implementation, they paged through the notebooks, pausing at the student work relevant to the discussion, then narrowed in on one page which contained the assessment, which was to be the focus of our work together. In this introduction, the team foreshadows a distinctive aspect of their protocol-guided sessions, namely, their use of formative assessment.

How Team PbRE Described Their January Implementation

At their January session, the team highlighted how they had changed the original assessment. They started by revisiting the original assessment, which they called a "test," used sentence starters and asked students to share their understanding of renewable, non-renewable and recyclable resources. The underlined portions of the transcript represent is what the students filled in:

> ***JANICE:*** *(reading from the low student notebook) 'Wind is the best renewable resource because it is available all over Minnesota and you can get everywhere and wind.' So they're missing the data. Let's see what this one says (reading from high student notebook), 'Wind is the best renewable resource because it produces the most energy and it is available in the areas we need it to be in Northern Minnesota.'*
>
> ***GEORGE:*** *That's what we wanted, available and produces the most energy was the language I was looking for.*

The team proceeded to share how they had modified it -- which I will discuss at length later in the analysis. It is worth noting here, however, ideas that foreshadow ideas about assessment that are central to the analysis. First, the *Looking at Student Work* protocol was designed to look at open-ended summative assessments that ask students to apply what they have learned, such as prototypes resulting from the engineering design challenge. The provided assessment lacked the complexity that the protocol was designed to interrogate. Additionally, one of the inherent structures of protocols is that they establish roles for participants, one of which is that the teacher presenting the student work is responsible for bringing in a scoring rubric, which the team did not do.

How Team PbRE Described Their March Implementation

Following protocol guidelines, the session began with the team providing a review of their implementation. The team emphasized what they had done both in terms of the content (wind turbine, energy) and pedagogical strategies (team-work, roles):

JANICE: *So, students built a wind turbine that would create the most energy.*

GEORGE: *And I think even before that team-building . . . We had a lot of team building that we did. Frontloading team-building.*

JANICE: *What is that called, roles.*

GEORGE: *Roles, the facilitator, doing all that stuff. The idea of no finger-pointing. J's mantra. That was heavy duty part of working together to establish that.*

JANICE: *Then we went into renewable.*

The team also discussed a modification to the protocol that will be discussed in depth later in the analysis, co-creating a scoring rubric for the unit. Three main assertions were revealed from the analysis of Team PbRE's *Looking at Student Work* sessions. Each assertion is supported with critical incidents from the protocol session data, which are representative of recurring issues that arose during the *Looking at Student Work* discussions.

Four main assertions resulted from analysis of Team PbRE's *Looking at Student Work* sessions. The following critical incident took place during the first *Looking at Student Work* session, and is a representative example of the team's process for developing a scoring rubric. The excerpt took place after the facilitator explained the protocol and the process for using it, to which the team asked if Alexa had brought the rubric or if they should create one. Since the team had not brought a scoring rubric, as called for in the protocol, Alexa suggested they create one using the student work they had brought.

Assertion 9

Flexibility in protocol use supports redesign of curriculum specific to assessment.

Critical Incident 9

> ***ALEXA:*** *You want to do that first [create rubric] then look at this [student work]? So we can use that to prepare for finishing the unit. Because this is just formative assessment, right? This isn't the cumulative.*
>
> ***GEORGE:*** *The cumulative thing will probably be. I mean, we're looking at the blades and how they revised it. And they'll have, like this class, they'll have a log sheet where it shows variables they adjusted, pitch, things like that . . .*
>
> ***JANICE:*** *Okay, so I'm trying to think, how would we break it [scoring rubric] down? By day?*
>
> ***GEORGE:*** *Well we know that it, I was just thinking about this writing prompt.*

ALEXA: *Why don't we just start with the writing prompt first?*

GEORGE: *We know that the writing prompt had them talk about, 'who needs what, why.' So we required that piece.*

JANICE: *Oh, ya, we had that on the board.*

GEORGE: *Um hm. We talked about that. Was that the engineering piece? Then what I would say is, to me it's almost like the engineering piece is who needs what why. The science piece is renewable and that the energy, it produced the most energy, right? That's another part of it right? Looking at maps?*

In this excerpt, the team was in the early stages of designing a draft of a scoring rubric. The decision to design a rubric was informed by two foundational premises of this study. First, the *Looking at Student Work* protocol calls for the use of predetermined criteria from which to communicate expectations to students, and evaluate student work. Second, the co-developed curriculum was being designed for other teachers to use, not just these teachers for their classrooms. As such, the curriculum required a rubric for future teachers of the unit. In the absence of these two foundational requirements for the protocol session, it was necessary to modify the protocol to accommodate the design of a rubric to create predefined scoring criteria for evaluation of the student work, and for future redesign and use of the curriculum. This critical incident provides insight into how the team's initial vague ideas about the "cumulative thing" were clarified through the process of creating the rubric. As they translated what they had done in their classroom, they revisited what they wanted students to know and do, and inform their understanding of what students had learned. In the excerpt, three topics of discussion arose early during the *Looking at Student Work* session: the nature of the assessment (formative assessment vs. summative assessment), how to organize (break down) the scoring rubric, and adjust their ideas about what content should be included in the scoring rubric (engineering, science, maps). These ideas show how the team conceives of the relationship between the curriculum and the student learning. The students' work the team brought was a formative assessment of their instruction as much as it was a reflection of student learning. Thus it informed how to approach creating a scoring rubric, and how the content they had taught was reflected in it. In the process, the team had expanded and elaborated upon these preliminary ideas. Thus, Flexibility in protocol use supports redesign of curriculum specific to assessment.

One of the ways facilitation contributed to curriculum redesign, beyond the creation of the rubric, is by raising the issue of assessment more generally. The process of co-developing the rubric not only shifted the team's thinking about assessment solely from a formative perspective, to a "cumulative thing," the protocol process ignited the team's efforts to clarify their goals for assessment, and helped the team articulate what content should be included in the rubric (and curriculum), bringing coherence to the curriculum and related activities associated with content. For engineering, "who needs what and why," and for science, renewable energy, and for mathematics, "maps." Figure 4.3 shows the first draft of the co-developed rubric.

Engineering: Build Wind Turbine blades
Science: Renewable energy & non-renewable energy, resources, recyclable
Math: Surface area, Measuring energy, Physical (conceptual), Numerical (mathematical), Angle measurement
Guiding Principles:
Team-building (group roles) – scrap the "lone genius" model
Language connections (WIDA scale):
Renewable, non-renewable, recyclable
Spin, rotation, energy, solar energy, process, angle
Variables: pitch, surface area, number of blades, shape
Rural, infrastructure

Know	Be Able to Do	Comments
Difference between renewable and non-renewable and recyclable	Measure angle Measure mass Work collaboratively	2 assessments: (testing w/ washers) and written letter, need to be viewed together because they can build without knowledge, but in conjunction with writing assignment. Both as a dual-post assessment then we have holistic view of understanding.
Variables affect outcome of solution Understand pitch, angle, Blade size	Intuitive understanding of variables in relation to the problem	
Geography of MN	Map skills to use key Rural and urban infrastructure Analysis of features of MN and relate to energy types (solar, wind & water)	Goal: understand the best type of energy for that area
Circuits	Complete circuit, connect volt reader	Build on prior lesson, this was a way to reinforce circuits lessons (not assess).
Water, wind and solar energy distinctions	Tools: solar panel is necessary for processing this type of energy Battery is where energy is stored. Wind need volt reader Water energy conceptually (see movement of gears – system) To produce energy requires movement, need energy to harness.	Investigate different materials for the water wheel energy output. Note: revealed a misconception regarding storing energy – where does energy go?
Knowledge of process (client letter, who for, why, why not other energy is better)	Use of academic language Connect evidence and explanation with reasoning	Qualitative and quantitative reasoning

Figure 4.3. This figure shows the first draft of a rubric with content, what students need to know, and do for the PbRE student artifacts.

Ultimately, the facilitator's shift in the use of the protocol guided what could have been an unproductive session, given the absence of a rubric, into an in-depth discussion about the type of assessments the team wanted to create for the PbRE unit, potential improvements for the assessment, and engaged in further discussion about what content and criteria to include in the scoring rubric. This critical incident foreshadowed how the conversations about the type of assessment, the decision to organize their assessment around a writing prompt, and content, triggered related conversations that helped the team think more deeply about assessment specific to their teaching context.

The following assertion and supporting critical incident took place during the second *Looking at Student Work* session.

Assertion 10

Coming to understand STEM assessment serves as a collaborative tool that mediates STEM PDC development.

Critical Incident 10

> ***JANICE:*** *So, I think that George and I were starting to get worried that with so much focus on the wind turbine that, that content would be lost, but when we took this [second draft of assessment] they did really well. Like, out of the five classes, I think I have four 5th graders who didn't pass.*
>
> ***ALEXA:*** *Is that typical?*
>
> ***JANICE:*** *No! I don't think so.*
>
> ***GEORGE:*** *From an ELL perspective, I will say that this [writing-embedded assessment] is much more difficult than say, like a multiple choice . . . I guess what I'm saying is for a lot of us we don't recognize the difficulty that an ELL student has with the writing. That's what I'm getting at. A student who may be*

very capable of giving us regurgitated information, or sort of giving us what we want when we give it to them in a format like that. When we give it to them like this and we give it to them open-ended, ESPECIALLY in this form, you see a lot of misconceptions start to pop up. So, even by just steering them, I mean this [draft of assessment] is a much more controlled document than this [original draft]. This would be, this was hard for a lot of the kids that were even smart. Let's see, what did we get? What was the highest score we got in here? We got a 12 out of 12 from Manning [name changed].

JANICE: *There were a lot* **. . .**

GEORGE: *So I think in some ways, this is still a problematic assessment because of the language . . .*

ALEXA: *So, having said that, could you speak to the value of this? Would you use it again?*

GEORGE: *I think so, because what we're getting at is that ultimately, kids are going to see this kind of stuff. And this is the kind of stuff that they see in Benchmark sometimes. That they need to know how to explain themselves using language and they need to understand what the question's asking them. Even though they're ELL kids, you can't get away from some of these words like produced. They are gonna know what you mean when you say, 'makes the most energy,' but produced is a word that is going to be problematic for kids that aren't used to it. So, words like that, I kind of, I don't shy away from because you know they're going to be there, you know?*

In this excerpt, instead of scoring the student work they had brought, the team went through a similar process of evaluating the student work, this time specific to English Language Learners (ELL). The team had redesigned the assessment they had brought to the first *Looking at Student Work* session, and the student work was in response to the prompt: *who needs what, why.* Rather than having students do a quick write in their science notebooks, the team had come up with a writing embedded assessment (WEA) that utilized sentence stems. Given that the team had not typed up the rubric they had designed in the previous *Looking at Student Wor*k session, it was necessary to modify the protocol again to further support refinement of the assessment, this time related to the implications of WEA for ELL students. In this excerpt, the team discussed a range of issues related to the WEA they had designed, shifting from considering how well the students did, to the challenges ELL students face with writing due to language barriers, and the reality that students are going to see writing-embedded tasks across their schooling.

While the team did not typically use open-ended writing assessments, they were happy with the performance of their students, and saw value in exposing students to academic realities of schooling because students cannot get away from unfamiliar language. The team was worried about content, and about the challenges WEA-type assessments posed for ELL students; yet, they also believed that WEA provided opportunities for students to be exposed to open-ended assessment that they would ultimately encounter in school. The team saw WEA as having value for exposing students to deciphering what a question is asking and for them to explain themselves.

The critical incident reinforces the notion that by remaining flexible, the facilitator supports development of assessment tools. In this case, by modifying the protocol. It also builds upon the understanding of how protocol facilitation strategies support collaboration and refinement of the curriculum by informing how coming to understand STEM assessment serves as a collaborative tool that mediates STEM PDC development specific to for ELL students.

The team used the student work to consider a subgroup of students and the effects writing embedded assessments (WEA) have on ELL students. This led to the team considering factors they had not previously considered specific to their teaching context and promote the development of STEM PDC. The purpose of using the *Looking at Student Work* protocol is to help collaborative teams stay focused on salient issues related to student learning. In this case, the team may not have followed the pre-established protocol norms of scoring student work individually, then collectively, before engaging in reflection and feedback, but the net effect of close analysis was achieved.

The following critical incident took place during the third *Looking at Student Work* session, and provides additional support for the assertion that coming to understand STEM assessment mediates STEM PDC development.

Critical Incident 11

> ***GEORGE:*** *I thought that would make more sense [to design the rubric together] because what we were thinking is what we have now would need to be pared down, so the rubric would ultimately be changed too . . . I almost think that the development of the rubric would inform it. It's almost like the backwards*

planning thing. What we want them to know goes back to what are we gonna take out? What are we going to pare-down . . .

This critical incident provides further support for how coming to understand STEM assessment serves as a collaborative tool that mediates STEM PDC development. In the previous critical incident, we saw how flexibility in facilitation led to redesigning the rubric, and helped the team consider the assessment needs a subset of students (ELL). George's idea that the scoring rubric could serve as a tool for the "backwards planning thing," illustrates a shift in the team's thinking away from individual lessons within the curriculum, toward a more cohesive process of curriculum design. Whereas in earlier sessions the team focused on using the student work they had brought to think about how students had done, or how to revise the assessment tool, in this excerpt, George was thinking about the relationship between the assessment t and the curriculum as a whole – how trimming down the curriculum and changing the rubric are linked. The development of the rubric would inform curricular modifications, and the "backwards planning thing" could help them think through what they wanted students to know and ultimately finalize the curriculum document.

The "backwards planning thing" is a reference to a strategy that approaches instructional design as a purposeful task analysis, logically inferring what teachers do in the classroom from the desired learning outcomes (Wiggins & McTighe, 2001; 2005). Considering the Stages of Backward Design model, within the context of George's thoughts about backwards planning and what took place during the previous *Looking at Student Work* sessions, provides insights into their professional judgements related to

STEM curriculum design. The first stage of Backward Design is to identify the desired learning results, which the team had clearly done during the first *Looking at Student Work* session when they developed the first draft of the rubric. They had also planned learning experiences and instruction during the summer PD, which they discussed the efficacy of during the previous *Looking at Student Work* sessions. What had been missing up to this point, was the middle stage of the backward planning process: determining acceptable evidence.

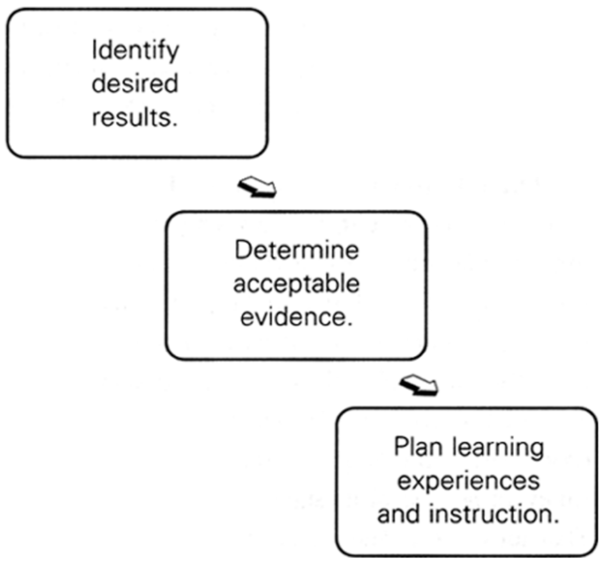


Figure 4.4. This figure shows the stages of the Backward Design model of curriculum development (Wiggins & McTighe, 2001, 2005). Backward Design image retrieved September 9, 2017 from http://en.wikipedia.org/wiki/Backward_design.

When George says, "*I almost think that the development of the rubric would inform it. It's almost like the backwards planning thing,"* he signals a shift in thinking about the unit as a whole, rather than one lesson or assessment tool. Specifically, how the rubric could help them align their assessment with the curriculum, and further clarify their goals for both the assessment and the lessons within the curriculum.

The following critical incident took place during the third *Looking at Student Work* session, and has two parts. The first part is an excerpt of the transcript, in which the team summarized the scoring criteria and discussed how it aligned with the integrated STEM curriculum. The second part is taken from the PbRE curriculum, and shows the three iterations of the assessment tools. Draft 3 of the assessment was the focus of this session.

Assertion 11

Combining iterative design of assessment tools with and evaluation of student work, affords adaptations and improvisations to the STEM curriculum.

Critical Incident 12

Part 1: Critical Incident *Looking at Student Work* Transcript

ALEXA: *. . .The other variables, it was pitch, surface area, and you had a third one that you focused on.*

JANICE: *The number.*

GEORGE: *Blades.*

ALEXA: *Oh, number of blades, that's it.*

JANICE: *Angle, pitch angle.*

ALEXA: *Alright, so I have (reading from session notes) "engineering challenge is building the wind turbine blade. Science is "renewable energy, non-renewable, resources, recyclable." For math I have, "surface area, measuring energy, physical" and in parentheses, "conceptual, measurement."*

JANICE: *And maybe angle.*

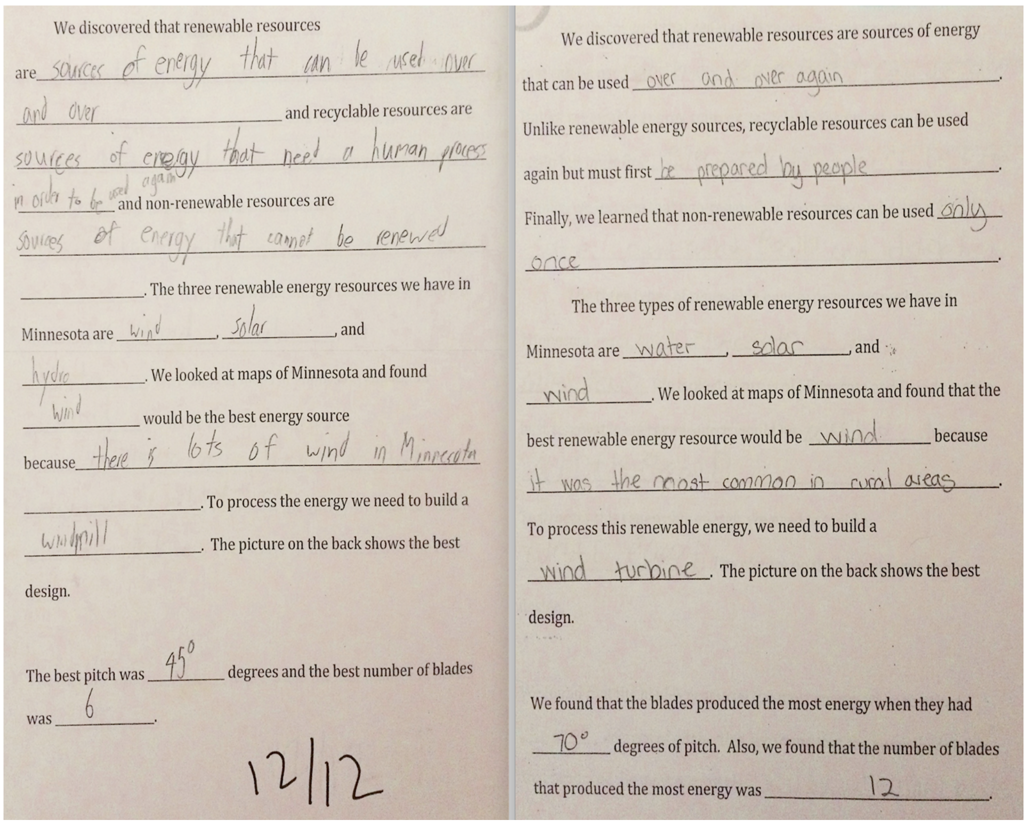
ALEXA: *And then in terms of guiding principles, the team-building and then language connections. I put in parentheses WIDA scale. Recyclable, renewable, solar energy, spin, rotation, process, wind, angle. And under variables I put pitch, surface area, number of blades. Okay.*

GEORGE: *Shape too.*

In this critical incident, the team summarized what they had identified as criteria for the rubric they would use for scoring student work. It illustrates how modification of the protocol, in this case, design of the rubric rather than scoring the student work, supported development of curricular resources specific to assessment. In addition, it shows how combining iterative design of assessment tools with and evaluation of student work, affords adaptations and improvisations to the STEM curriculum.

The process of designing the scoring rubric supported refinement of the team's assessment ideas in several ways. First, the decision to modify the protocol created an opportunity for teachers to identify the knowledge and skills students must have to be successful with the engineering design challenge. Second, the process helped the team talk through how the content they identified aligned with their integration goals for the unit. Third, flexible facilitation helped the team identify academic language that needed modification for ELL students. Specifically, the team aligned key vocabulary terms with the World-class Instructional Design and Assessment (WIDA) scale (WIDA Consortium, 2014). WIDA refers to the English Language Development Standards developed by educators and educational leaders in WIDA Consortium member states, and aligned with states' content standards (WIDA Consortium, 2014).

____________________ is the best ______________________ resource because ____.


We discovered that renewable resources are sources of energy that can be used over and over and recyclable resources are sources of energy that need a human process in order to be used again and non-renewable resources are sources of energy that cannot be renewed. The three renewable energy resources we have in Minnesota are wind, solar, and hydro. We looked at maps of Minnesota and found wind would be the best energy source because there is lots of wind in Minnesota. To process the energy we need to build a windmill. The picture on the back shows the best design.

The best pitch was 45° degrees and the best number of blades was 6.

12/12

We discovered that renewable resources are sources of energy that can be used over and over again. Unlike renewable energy sources, recyclable resources can be used again but must first be prepared by people. Finally, we learned that non-renewable resources can be used only once.

The three types of renewable energy resources we have in Minnesota are water, solar, and wind. We looked at maps of Minnesota and found that the best renewable energy resource would be wind because it was the most common in rural areas. To process this renewable energy, we need to build a wind turbine. The picture on the back shows the best design.

We found that the blades produced the most energy when they had 70° degrees of pitch. Also, we found that the number of blades that produced the most energy was 12.

Figure 4.5. This figure shows three iterations of the assessment the team brought to the *Looking at Student Work* sessions. The original assessment (top), the second draft (left) and the third draft (right).

As shown in Figure 4.5, each iteration of the assessment encompassed more content and skills from other lessons within the unit. Whereas during the first iteration of the assessment, the team had identified a very narrow aspect of the curriculum the team wanted their students to be proficient with: wind is the most efficient renewable resource and, therefore, was the best choice to power a mobile hospital in Northern Minnesota. In the second iteration, the team and expanded these ideas considerably, having determined how each of the criteria aligned with the content that was being integrated in the wind turbine design challenge. The final iteration of the assessment included attention to academic language for all students, but especially for ELL students. In summary, the team's notions of STEM PDC could be summarized as having expanded to include assessment as a critical component of curricular resources that includes the following aspects of assessment criteria: (i) Variables: pitch, surface area, number of blades, and blade shape. (ii) Engineering: building the wind turbine; (iii) Science: renewable, non-renewable, recyclable resources; (iv) Mathematics: surface area, measuring energy (physically with washers and conceptually with work); (v) "Guiding principles" of the engineering design process: teamwork and academic language.

Analysis of the *Looking at Student Work* discussions and analysis of the progression of changes made to the assessments, reveal an interesting pattern: with each adaptation to the assessment tool, the assessment captured more of the content the team had taught throughout the unit, and the assessment itself was beginning to look more like a scientific explanation. A scientific explanation has a claim-evidence-reasoning (CER) form, where a claim is supported with evidence, and the two are linked with reasoning (McNeill & Krajcik, 2011). In this example, the claim is: "wind is the best natural resource." The evidence is from the map analysis lesson, "because there is lots of wind in Minnesota" for the student on the first draft, and "It was the most common in rural areas" for the student whose work is reflected in the second draft. In addition, students had to share their best wind turbine prototype in the form of a drawing, making a claim about the "best" prototype, and support their choice with data from the engineering design variables they had changed, pitch and blade number being supporting evidence. There were still some problems with the assessment in terms of functioning as a claim-evidence-reasoning format. For example, there was no way to actually check the accuracy of the evidence the students drew upon because they had not collected data on the variables they changed. Nor was there an attempt to have students link their claim and evidence with reasoning. However, modifying the protocol use to allow for collaborative design of the rubric informed the changes to each iteration of the assessment and, as such, reflect the team's evolving knowledge of STEM assessment.

This critical incident also demonstrates how the knowledge and skills discussed during the *Looking at Student Work* session are ultimately reflected in the summative assessment. The content is largely the same as draft 2, but with greater attention to decreasing the ambiguity of academic language for ELL students and asking the students to provide a reason for their response. For example, compare drafts 2 and 3:

Draft 2:

We looked at maps of Minnesota and found _______ would be the best energy source.

Draft 3:

We looked at maps of Minnesota and found that the best renewable energy resource would be ________ because __________.

Draft 3 makes it clear that the expected answer is not simply the "best energy source," but the best renewable energy source, taking away any ambiguity. It also asks for a reason, "because ______." Not only does having the students provide a reason for their answer function to push student thinking beyond a one-word answer, it also serves to make student thinking visible, which can provide teachers with a way to formatively assess student understanding. The assessment was taking on a more integrated structure, attempting to assess the science, the mathematics and the engineering prototype. In this sense, the assessment was evolving into a design-based form. Design-based discursive practices are fundamentally different from scientific practices (Azevedo, Martalock & Tugba, 2014).

Collectively, the critical incidents from Team PbRE's *Looking at Student Work* sessions illustrate how modifying the protocol to meet the teachers where they were in their understanding of STEM curriculum, serves to accommodate refinement of curricular tools related to assessment, allowed this collaborative team to consider aspects of their curriculum they had not initially considered. Modifications to the protocol allowed the team to re-evaluate their conceptions of assessment, to consider aspects of writing-embedded assessment on ELL students specific to their teaching context, the time and space to return to the backward planning process they had learned during the summer PD and apply to the post-implementation curriculum, and align key academic language with WIDA standards, and make the connection between curriculum design for themselves, and the use of the Understanding by Design framework to consider the cohesiveness of the lessons related to assessment.

The following critical incident provides additional support for the connection between iterative design and evaluation process.

Part 2: Critical Incident *Looking at Student Work* Transcript

The following critical incident took place during the third *Looking at Student Work* session, immediately following George's suggestion that collaboratively designing the rubric would allow for a backwards planning approach to curriculum redesign. In the excerpt, the team is identifying the knowledge and skills students would need to know for success, as proscribed by the *Looking at Student Work* protocol.

> ***GEORGE:*** *That's the one thing we would take out though [blade shape variable], because we figured it was difficult. Going forward, if we're going to have them measure surface area, when you have blades that are just free-handed and you're cutting them and they're not all uniform, it gets really difficult. So we talked about how we would have to have them uniform. Either use 90 degree angles or something that would work.*
>
> ***JANICE:*** *Or shapes that you can find the surface area with 5th grade math skills.*
>
> ***ALEXA:*** *. . . So let's then talk about, in terms of these things, what students would need to know and be able to do. So, what do they need to know to be successful?*
>
> ***JANICE:*** *The difference between renewable, recyclable and non-renewable.*
>
> ***ALEXA:*** *Actually, I'm going to put a table in here because I'm going to share this with you. Then we'll have the notes.*
>
> ***GEORGE:*** *Ya, because there's really like two assessments, right? There's this (pointing to the student work they brought), which they need to know that stuff for. But really, I'm just thinking about, do I need to know that [science content] if I make a blade and it worked and it picked up 116 washers? Could I still turn*

around and say, 'I don't know what renewable, recyclable and non-renewable is?' Probably. So, really it's a combination of the stuff on this, which guarantees that they know that. Then, in addition, you need to know how to work together in a group and build a wind turbine . . . I'm just saying the two assessments kind of have to be viewed together.

JANICE: *Our client letter said they needed to build a mobile hospital through a renewable resource. Then you have to know the renewable resource and know wind. You had to look at the map to know wind was the one to choose. Then after knowing wind, now I can go build the wind turbine. So, they kind of built on each other.*

GEORGE: *I guess I was just trying to imagine somebody who just kind of drifted through that and just got into the building. I might not know, or if I arrived late, I can still be building a turbine and not know that stuff. But if I'm expected to write this at the end, then I do need to know that, right? Because we say clearly, what is recyclable? So I guess what I'm saying is if we use these, if we talk about these two assessments about the building of the turbine and making it pick stuff up is one assessment, then this written assessment, if we look at them as a dual post-assessment, then I agree with you. They have to know. If we start looking at them separately, then I think, you know what I mean? So we have to say that this assessment goes together with the building of that thing and then, yes. You need to know that recyclable and renewable means.*

In this excerpt, the team had identified a problem with the engineering design challenge. Namely, having students calculate surface area of the wind turbine blades was problematic because student groups made random shapes. To fix this, the team decides the blade shape must be "uniform" and have "90 degree angles" that are measurable with "5th grade math." As the team discussed what students must understand in order to be successful in the engineering component (blade design), George realized that the assessment they had designed was more about the science content (renewable, non-renewable, and recyclable) and related academic language what the students need to know for the writing-embedded assessment). The realization led George to suggest that they write an assessment that captures both requirements, a "dual assessment." Janice argued the concepts build upon each other, to which George argued he can imagine a student building the wind turbine blades without understanding the science (or mathematics) behind it. In short, the team was discussing integration and how the assessment, as written, does not reflect integration of science and mathematics into the engineering design process.

The goal of an integrated approaches to STEM curriculum is to design engineering design challenges that require students to use mathematics and science to inform the students' design solutions (Moore, Tank, Glance & Kersten, 2013). As such, the team wanted to avoid "tinkering." Though neither George nor Janice say so explicitly, George's suggestion of a "dual assessment" can be interpreted as evidence of their PDC development -- their evolving understanding of how to integrate mathematics and science into the engineering, and how to effectively capture it in a summative assessment. Through a combination of designing assessment tools and repeated evaluation of student work during the *Looking at Student Work* sessions, his suggestion for a "dual assessment" reflected a desire to ensure students are not merely "tinkering," but using their understanding of mathematics and science, and that these understandings are aligned with the summative assessment.

This excerpt suggests that, prior to the *Looking at Student Work* session, the team had identified aspects of the curriculum that did not work as they had hoped during implementation. Specifically, they felt that not requiring students to use "90 degree angles" that could be used to calculate surface area with "5th grade math" was problematic. The *Looking at Student Work* session revived this conversation. The act of using the student work they had brought to make the scoring rubric for the summative assessment triggered a new way of thinking about their earlier observations -- how to reflect their integration goals in the assessment. In the excerpt, Alexa is actively recording the team's ideas for what skills and content knowledge they want reflected (I'm going to put a table in here because I'm going to share this with you. . .), when George makes the connection between their earlier observations about surface area calculations and what is reflected in the assessment they brought and what is missing from the assessment that would more accurately reflect integration (and what they taught).

This critical incident provides insight into how the team's thinking evolved from creation of assessment for a single aspect of the curriculum (science) into a summative assessment that aspires to integration of multiple content areas that had been taught over the course of the unit (science, mathematics, and blade design).

The following assertion and supporting critical incidents shows how adaptations and improvisations to STEM assessment informed other lessons within the unit, and how the teachers used the ideas raised during the collaborative discussion to adapt and improvise the final curriculum and corresponding summative assessment.

Assertion 12

Improvisations to STEM assessment mediate adaptations to other lessons within the STEM curriculum and inform STEM PDC development.

Critical Incident 13

Part 1: Critical Incident *Looking at Student Work* Transcript

ALEXA: *All right, and the last one is 'we found that the blades produced the most energy when they had 70 degrees of pitch and the number of blades.' So this is the variable one. What would the correct response to this be?*

GEORGE: *It's the piece that they get the right answer as long as you kind of give a number, because we didn't ever come up with a pitch that we viewed as better than other pitches. In other words, we didn't isolate or identify that 70 degrees of pitch was the best for all groups. So, one group with 15 degrees of pitch might have had a model that worked great and another one might have had 70 work great. All we wanted to see is if they put a question like this, will that force them to know how to measure it and would they take an interest in knowing what the pitch was. That's kind of why we put that in there.*

ALEXA: *How could we, let's come up with a four [scoring level] if we reword this question.*

JANICE: *I think you'd almost have to give one of those example questions like,* *George wants to build a turbine. George's first design wasn't good. George's first design had this pitch, and this many blades. Then George decided to change the number of blades and the angle of the pitch. Now, George's wind turbine picked up more washers. Why did George's? and to see if they could draw the conclusion that, 'wait, George did a bad experiment. George changed too many variables.'*

ALEXA: *What do you think, George?*

GEORGE: *Only doing one variable at a time, which would be an engineering principle, I guess . . .*

ALEXA: *So you guys did group data on this. What about going back to what you said earlier about having two assessments? Having a dual assessment, you called it. Could you assess this piece at that time?*

GEORGE: *It would certainly be a better assessment to watch a kid have to show us the pitch than to just put it down in there. Because again, as long as I put this, if I put any number here, I got this question right. Because all we want to see is that they knew what the pitch was . . . I would have an assessment where, 'show me that you know how to measure the pitch.' Show me on a piece of paper. Like, we can even have something like this. 'Fill in 50 degrees of pitch or fill in an angle that has,' something like that. You can have three options where you're going to show me 30 degrees of pitch. Now, decrease that to 20. Something like that. Where maybe it would still be on a paper/pencil type of test, but it would have now become something where I'm looking at a visual of that members and okay, this is 70, he wants me to put it. You know what I mean?*

In this excerpt, the team had identified four assessment criterion: renewable and non-renewable energy, variables, mapping analysis, and data analysis, and were discussing how to define each level of understanding within the rubric. The team focused on one question in the summative assessment they had created, and had identified a potential obstacle to assessing student understanding of the relationship between the number of blades and pitch that produced the most energy. As a result, the teachers could not tell when they looked at a student's answer what the student actually understood about how to use mathematics and science to inform the EDP. To resolve this problem, the team discussed a number of new assessment strategies including: creating a scenario that illustrated student understanding of the role of variables in their engineered designs, using some of the students' data to compile a set of group data that could serve as common data set for the assessment, and creating a performance-based component to the assessment, similar to a lab practicum where students manipulate a physical model to demonstrate their knowledge of how the variables effect the number of washers the model can lift. When the conversations are viewed in relation to the changes made to the curriculum, the analysis reveals how design of assessment tools combined with repeated evaluation of student work supported adaptations and improvisations to the curriculum.

The following critical incident provides further evidence for the assertion that improvisations to assessment influenced other lessons within the curriculum. It shows the final draft of the assessment resulting from the iterative evaluation and redesign of assessments and scoring rubrics.

Part 2: Final Summative Assessment for STEM Curriculum

Unit Post Assessment

Students will individually complete the letter below. The letter is a response letter to the client lettin[g] them know what they have learned about renewable energy in Minnesota and wind turbines.

Dear Medtronic and University of Minnesota,

We discovered that renewable resources are sources of energy that can be used ____. Unlike renewable energy sources, recyclable resources can be used again but must first ____. Finally, we learned that non-renewable resources can be used ____.

The three types of renewable energy resources we have in Minnesota are __________________, ____________________, and ______________________. We looked at maps of Minnesota and found that the best renewable energy resource for the mobile hospital would be ___________________ because ____ ____.

To process this renewable energy, we need to build a ___________________________ _______________________________. The picture on the back shows the blade design that our engineering group learned produced the most energy. We found that the blades produced the most energy when they had ______________ degrees of pitch. Also, we found that the number of blades that produced the most energy was ______________________________________.

Figure 4.6. This figure shows part 1 of a two-part final version of the summative assessment the team co-designed. Part 1 assesses understanding of the science content of the STEM curriculum.

This critical incident combined with the changes to the four iterations of the STEM assessment tools provide evidence for how improvisations to STEM assessment mediate adaptations to other lessons within the STEM curriculum and inform STEM PDC development. The most significant change from previous iterations was that the final version now had two parts, the original writing embedded assessment (WEA), and a second part where students are provided with a set of hypothetical data and asked to draw conclusions from the data. In short, the summative assessment has been transformed into a “dual assessment.” In the previous critical incident, George had argued that the WEA reflected students’ knowledge of renewable, non-renewable, and recyclable resources (science). He also argued that the assessment lacked a way to evaluate student knowledge of “building things,” (engineering)and the mathematics (surface area) and teamwork (EDP). He argued for a “dual assessment” that would bring together the engineering of the wind turbines with knowledge of what recyclable, renewable and nonrenewable means. The summative assessment in the final curriculum accomplishes this goal. Part two of the summative assessment was an attempt to address these content-alignment issues. This illustrates development of their STEM PDC, as they moved from assessing their knowledge of the science to assessing students’ knowledge of integrated STEM PDC.

In part 2 of the summative assessment, students are presented with a set of hypothetical data that reflects the relationship between the variables tested during the design challenge (pitch, number of blades, surface area of blades) and asked to find the average of each trial, and compare how degrees of pitch relates to wind turbine energy production (see figure 4.7). Thus, the final assessment not only evaluates student knowledge of the design challenge, it introduces an analytical component that had been absent in previous versions of the summative assessment. Students must look at the data and recognize that the surface area and number of blades are the same, and conclude which pitch (blade angle) produces the most energy (lifting the most washers).

Next, look at the data below that a group from a different school collected about the pitch from their design. Find the averages in each of the two trials and then and write a note to the group to give them advice about what you think they should do with the pitch in order to produce more energy.

Hypothetical Group's Data

Trial 1	Pitch 30 degrees	8 blades	25 inches of surface area	Test 1 15 washers lifted	Test 2 16 washers lifted	Test 3 15 washers lifted	Average
Trial 2	Pitch 50 degrees	8 blades	25 inches of surface area	Test 1 8 washers lifted	Test 2 10 washers lifted	Test 3 9 washers lifted	Average

Figure 4.7. This figure shows part 2 of the two-part summative assessment the team improvised for the final version of the Powered by Renewable Energy STEM curriculum. Part 2 assesses the engineering and mathematics components of the curriculum.

Brown & Edelson (2003) conceive of curriculum use as an act of design, and the process of improvising (as well as offloading and adapting) as a function of the teacher-curriculum relationship -- through the use of curricular tools (Domain Representation, Task Representation, and Physical Object Representation) and personal resources (Pedagogical Content Knowledge (PCK), Subject Matter Knowledge, and Teacher Beliefs and Goals), teachers develop new understandings that supports development of PDC. How team PbRE perceived and mobilized resources to achieve their curricular goals has everything to do with the interactions between their classroom experiences, development of assessment tools, and examination of student work during the *Looking at Student Work* conversations. During these sessions, the team wrestled with what worked, what did not work, and shared their ideas for how to improve the assessment tools. The evolution of how Team PbRE perceived and mobilized curricular resources related to assessment is reflected in each iteration of the assessment.

Whereas the team initially relied heavily on their learning from the summer PD (client letter, sequencing of lessons, Hexbug design challenge that is the focus of Lesson 1), over the course of the three *Looking at Student Work* sessions, the team's ability to perceive and mobilize increasingly complex integration goals was evident. To be fair, when the team wrote the original curriculum, there were no pre-existing curricular resources for the team to "perceive and mobilize" because the summer PD had not emphasized assessment; nor had the team worked through ideas for a summative assessment when they designed the original unit. As such, design of the assessment became an iterative process of trying out ideas in their classroom, using informal, formative assessment to see how students did, and discussing what happened and how to improve upon it during the *Looking at Student Work* sessions. The process of designing an assessment and scoring rubric to accompany it, served to develop the team's pedagogical design capacity – their competence for integrated STEM assessment. Thus, their use of student work and development of assessment tools changed significantly over the course of the three *Looking at Student Work* sessions, as reflected in the improvisations they made to the summative assessment. Much like weaving a tapestry, the design of curriculum assessment tools was woven together with repeated evaluation of student work that is the result of the co-designed tools. The intersecting "threads" passing in one direction at right angles to each other, improvising a new "cloth" that reflect the team's developing STEM PDC.

The following assertion and associated critical incident provides further support for the assertion that the combination of designing assessment tools and repeated evaluation of student work lead to adaptations to within other lessons of the unit.

Critical Incident 14

The following critical incident has two parts, an excerpt of the transcript from the third *Looking at Student Work* session, and a visual of the modifications made to Lesson 6 of the final PbRE curriculum. The excerpt took place toward the end of the third protocol-guided session as the team had finished creating the rubric, printed it, and prepared to use it to score the student work the team had brought.

ALEXA: *Let's just give it [scoring student work with the rubric] a try.*

GEORGE: *Well, I'm at a loss, I'm just gonna tell you right now.*

ALEXA: *Are you?*

GEORGE: *Yeah, kind of.*

ALEXA: *Do you want to do one together first?*

GEORGE: *I think that would help me anyway.*

ALEXA: *Okay, let's do it.*

GEORGE: *I don't do as much grading as you guys do.*

ALEXA: *No, these rubrics are subjective.*

GEORGE: *Just with a flawed document like this (gesturing to it's hard.*

ALEXA: *You're being hard on yourself. I'm not supposed to impose my judgment but I think this is a nice assessment.*

GEORGE: *I think it's a good start. I just think it needs help . . .*

ALEXA: *So, reusable, over and over again. Renewable, only once. Perfect. In an ideal situation, right?*

GEORGE: *In a four.*

ALEXA: *Yes. And that doesn't mean they don't know it. It just means there's no evidence of it here that we can see.*

GEORGE: *What it means is, if I said, if the kid says, you have to do something to it first, it doesn't need to process. It's clear that he understands, he or she understands the process, he just didn't use the word.*

JANICE: *Kind of process without vocab, but has understanding.*

GEORGE: *But clearly understands.*

ALEXA: *Yeah, so here, they're really using the academic language and here, it's conceptual understanding.*

GEORGE: *Which is fine, but they didn't quite [get it], let's take it to the next* *level which we would consider a four. It's perfect. This is language, this is the concept, this is everything.*

ALEXA: *Demonstrates conceptual understanding.*

GEORGE: *Then we're done with the language portion because the language can't give you a score. If I use the language correctly but I have no clue what I did, I don't get any points for that?*

ALEXA: *Yeah. And then over here, that's--*

GEORGE: *I like that.*

ALEXA: *Then here it's not only conceptual understanding but use of academic language to support it.*

GEORGE: *This is why I said I think we kind of have to have a rubric before we, before I, can start to understand what we could pare [down], what we could get out of it.*

In this excerpt, the teachers were preparing to score the student work they had brought when George announces he is "at a loss." While George was initially resistant to scoring the student work, the realization that "the language can't give you a score," informed his understanding of how the scoring rubric and the assessment work together. This new awareness helped to shift the team's goals. When the team started thinking about the scoring rubric and the assessment in terms of a process of the "backward planning thing," their thinking shifted. After redesigning the summative assessment discussed in the previous critical incident, the team realized that the conceptual connections they had made to what they had actually taught, should be reflected in the earlier lessons. Table 4.5 shows the original data table *Lesson 6: Student Designed Windmill Experiment* of the STEM curriculum. Figure 4.6 Shows the final version of the data table in *Lesson 6: Student Designed Windmill Experiment*.

Table 4.5. *Data Table from Lesson 6 of the Original Powered by Renewable Energy Curriculum*

Design #	**What did You Change?**	**How Many Washers?**

Table 4.6. *Data Table from Lesson 6 of the Final Powered by Renewable Energy Curriculum*

Trial	**# Blades**	**Surface Area**	**Pitch**	**Washers Test 1**	**Washers Test 2**	**Washers Test 3**	**Average**

Analysis of lesson 6 focused on two components of the team's Lesson: blade shape variable and data collection table, which produced two significant adaptations that can be traced back to improvisations made to the summative assessment in Lesson 7: (i) they added a constraint to the blade shape variable; and (ii) they changed the data collection process the students used during the prototyping of wind turbine blades. Whereas the original data table only asked students to record what they changed and how many washers their design lifted, the final data table called out the variables of interest: number of blades, surface area, and pitch. Thus, the modifications made to the final data table in lesson 6 made explicit connections to the summative assessment students would ultimately be responsible for. In the original version of lesson plan 6 the teachers used guiding questions related to number of blades, pitch of blades, blade shape, and size of blades to direct student prototyping. The prototype design was to be followed by testing the prototypes to determine which design lifted the most washers, and the data table provided space for students to record the prototype number, changes made to the prototype, and number of washers lifted.

In the final version of lesson 6, the teachers significantly changed how they guided students, directing students to collect and record data in alignment with the guiding questions: number of blades, pitch of blades, blade shape, and surface area. Note "size of blades" has been operationalized to "surface area." Recall that in Critical Incident 16 the team had talked about how the lack of uniformity made it difficult to measure and compare blade prototypes, and how they planned to adapt their lesson to make it easier to calculate surface area "with 5th grade math" by using "90 degree angles." These ideas manifested themselves in the change from "size of blades" to "surface area," as well as to the type of data collected in lesson 6.

Comparing the original and final versions of *Lesson 6: Student Designed Windmill*

Experiment, I have shown how the improvisations to the assessment eventually lead to adaptations to lesson 6. When the *Looking at Student Work* conversations are viewed in relation to the changes made to the curriculum, several aspects of those changes demonstrate how design of assessment tools with repeated evaluation of student work facilitates adaptations and improvisations the STEM curriculum including: (i) improvising the summative assessment through integration of science (renewable, non-renewable, recyclable) and mathematics (surface area) into the engineering design process (blade shape variable); (ii) identification of an adaptations to lesson 6; and (iii) evolution of the team's approach to curriculum design from curriculum for self toward curriculum for others. Throughout the process, the team actively engaged in designing assessment tools and how repeated evaluation of student work facilitates improvisations and adaptations to the STEM curriculum -- as well as their PDC. The subject of the following analysis is the *Thinking Through a Task* protocol-guided session.

Team PbRE *Thinking Through a Task* Assertions and Critical Incidents

The literature on engaging teachers in curriculum design suggests that, while teachers regularly act as curriculum designers (Brown & Edelson, 2003), and have "generic design expertise" for enactment of curriculum, they lack "specific design expertise" for how to sequence curricular materials and operationalize curriculum reform ideals for knowledge and skill development (Huizinga, Handelzalts, Nieveen & Voogt, 2014, p. 36). In order to support teachers in the transition from enactment of their co-developed curriculum, to acting as designers of curriculum for other teachers, the *Thinking Through a Task* protocol was intentionally designed to consider aspects of "specific design expertise" teachers do not typically need to consider for enactment of curriculum into their own classroom.

The protocol was designed so that teachers, prior to rewriting the final curriculum, would think about their co-developed curriculum beyond the scope of their own classroom. The protocol intentionally focuses on curricular issues beyond what activities to do, including prompts that help teachers think about Best Practices -- how to provide feedback, support academic language, assess learning, and integrate science and mathematics into engineering, etc. Like the original protocol, the adapted protocol addresses goals and in-process supports. However, the adapted protocol differs from the original protocol designed by the University of Pittsburgh in that it specifically addresses integration of multiple disciplines and modifications to the original curriculum. The adapted *Thinking Through a Task* protocol explicitly asks teachers to consider how feedback and assessment can inform integration of science, mathematics, and engineering, the purpose of which was to ensure the team addressed integration. The most significant adaptation to the protocol is that it explicitly prompts teachers to address any modifications to their original curriculum they made during implementation. The purpose of this adaptation was to ensure teachers share the different modifications each made during implementation (see Appendix B).

The protocol was used with each team at the beginning of the final curriculum writing session to facilitate collaboration and refinement of the curriculum to support development of STEM PDC. The following assertion and supporting critical incident, illustrate the role the facilitator takes to support teachers in shifting from focusing on curriculum for themselves toward curriculum designed for use by other teachers.

The following critical incident took place after all of the *Looking at Student Work* sessions as the team discussed the *Thinking Through a Task* protocol prompt that asked about in-process supports (use of academic language, skills, and content). In the excerpt, the facilitator was attempting to get the team to consider how to write the curriculum in a manner that considered the needs of other teachers.

Assertion 13

Directive facilitation strategies push the teams to move beyond thinking of curriculum design for their own classroom only, and consider curriculum design for other teachers.

Critical Incident 15

> ***ALEXA:*** *What about (reading), "What are the ways students will use academic language skills and content?"*
>
> ***JANICE:*** *I said they use their science notebooks, that they're using the academic language within their groups, as they are with each other.*
>
> ***GEORGE:*** *Um hm. We had them talking in their groups as they, we gave them the way to talk about these things. Then we walked around and expected to be talking about them.*
>
> ***JANICE:*** *Ya, I said, we do a lot of checking in.*
>
> ***GEORGE:*** *Ya, so if I walked around and somebody said, if we give you a tool to measure pitch and they're talking about how they need to move it this way or the other way (gesturing), I would expect them to use the word pitch. So, they're saying, what degree of pitch do you need? Is it negative or positive? So, we got*

them talking in that way . . .

ALEXA: *The other thing I'm thinking about here, is how you have them start and end on the rug, where does that fit in for the whole class discussion?*

GEORGE: *I think that's a check-in process. We want to introduce something, have them go out, figure some things out and then have them come back and report back what they did.*

ALEXA: *So, I feel like that belongs in here somewhere.*

JANICE: *Yeah, like--*

GEORGE: *It's another form of expecting language to be used, right?*

JANICE: *It's how we structure our lessons.*

ALEXA: *The reason I bring some of these things up, is as you're moving forward in designing this curriculum, now you need to use your classroom and your experience, but also I'd like to push you to think about other people using this. Because you do a lot of things really, really effectively that I think need to be made explicit, because all those little things make it successful. It's not really just the activity, it's how you do the activity.*

JANICE: *Ya, that makes sense.*

GEORGE: *Um hm.*

ALEXA: *I think that morning meeting in the beginning and then after the activity reflecting, should—*

JANICE: *Check-in and check-out.*

GEORGE: *It's kind of an intro and a conclusion I think.*

JANICE: *Ya.*

ALEXA: *I think it's really important. You're bookending the day with discussion, with questions and reflection. So, when you redesign the curriculum that would be great to think about other people using this.*

In this excerpt, the team responded to the in-process support prompt related to academic language by listing things they did during the implementation of their curriculum: use of science notebooks, informal check-ins with students, and establishing the expectation that students use vocabulary during small group discussion. Listing what they did is an example of writing curriculum for their own classroom, rather than engaging in design of curriculum for other teachers. At the same time, teachers have not been trained as curriculum designers for others, and the lack of design expertise can negatively affect the quality of the designed curricula (Huizinga, et al., 2014). As such, it is not surprising that teachers' default to designing curriculum first and foremost for themselves, rather than with other teachers and classrooms in mind. The protocol intentionally focuses on curricular issues beyond what activities to do, but the protocol session also depends on the facilitator's ability to read the team, and help them shift their focus from their own classroom toward thinking about what other teachers -- especially those without STEM experience -- might need to understand in order to successfully use the PbRE curriculum.

This critical incident illustrates how the facilitator must strike a balance between following the lead of the team and steering the them toward thinking about the curriculum needs of other teachers. In this case, Team PbRE has extensive expertise with supporting academic language development. For one thing, George is an ELL teacher, and the team talked extensively during the previous *Looking at Student Work* sessions about connecting key vocabulary terms to WIDA levels, effectively integrating accessible and relevant academic language into their assessments, and establishing important routines to support academic language development (use of science notebooks, and classroom expectations for language use); yet the team does not initially address these aspects of Best Practices for supporting academic language development, skills, and content knowledge that could be helpful for other teachers.

In this instance, Alexa recognized the need to push the team to consider making their classroom practices explicit for other teachers. When Alexa points out the classroom routine that the team used to begin and end class with, she used the team's own practice as a launching point for raising the team's awareness that writing curriculum for others is distinct from writing curriculum for themselves. The *Thinking Through a Task* protocol initiates more formal aspects of curriculum design (use of academic language, providing feedback, using feedback, etc.) than the team had focused on during the *Looking at Student Work* sessions. As a result, the facilitator plays an important role in balancing active facilitation that steers the team toward thinking like curriculum designers for others, and more passive facilitation that honors the team's ideas, knowledge, and classroom experiences.

This critical incident illustrates how using a combination of non-directive and more directive facilitation strategies steered the team to think beyond their own classroom, and consider the needs other teachers might have for using the curriculum. It also illustrates the role directive facilitation strategies are sometimes necessary to push the teams to move beyond thinking of curriculum design for their own classroom only, and consider curriculum design for other teachers.

The following critical incident provides further support for the assertion that using directive facilitation strategies are sometimes necessary to push teacher to consider curriculum design for other teachers.

Critical Incident 16

ALEXA: *How will you provide students with feedback on their use of science and math to solve the engineering design challenge?*

JANICE: *I wrote, in their notebooks. I also put again, just the way we structure our class. We're not up there teaching, we're checking in on them all the time. So, when I check in with them and I say, 'look at your variable for surface area, how'd you find that?' If they can't tell us then, okay. So, well, 'how will we find the surface area then?'*

GEORGE: *One of the things I liked about it [the unit] too, was that I felt like our design challenge enabled them to have a lot of self-feedback. So, we didn't have to be sitting there and saying, 'did that work?' 'That didn't work,' or anything else because they were the one's going and saying, 'okay, that didn't work, now I'm going to try this.' We probably missed out on some times where they could have reflected maybe, if we had some sort of way to have them reflect after every single revision. Something like, 'what did you do next?' 'Why did you do this?' But there was a lot of just feedback going on, where they just tried something and* *then it either worked or it didn't . . .*

ALEXA: *Ya, so I'm wondering as you guys are talking, about how you will make that explicit in the curriculum?*

GEORGE: *How we would make our feedback explicit?*

ALEXA: *Ya, because a lot of your feedback was through discussion and through the peers giving each other feedback. We know it was there, but in terms of writing a curriculum, how do we make that visible? A little bit like the earlier discussion about the other things you do . . .*

JANICE: *You almost have to kind of front-load. Say, 'when you're teaching this teach it in a 55 min. block. You're going to start with your 10 minutes, and end with your 10 minutes (laughing). Do a checking in with your groups while they're working.'*

GEORGE*: We revise, 'name three revisions that your group did in order to improve the pitch or the angle.' You know, we'd have to start breaking it down into questions like that I think.*

ALEXA: *Ya, almost reflection, like you were saying a minute ago.*

JANICE: *Do we put that somewhere in our curriculum?*

ALEXA*: Ya.*

JANICE: *When we taught this, this is the format you want to teach it in.*

ALEXA: *I think so. I think be really specific. I think your curriculum is in really good shape, I don't think it should be much and maybe it's notes to teachers or maybe it's scaffolding supports, I'm not sure, but I think there's a lot of really* *good stuff that happens in your class that I'd like to see make it into the curriculum. You know?*

JANICE: *Ya, that makes sense. I didn't think about that.*

This excerpt illustrates the assertion that using directive facilitation strategies are sometimes necessary to push teacher to consider curriculum design for other teachers, and how the *Thinking through a Task* protocol afforded it. The prompt was designed to get teachers thinking about two aspects of the curriculum: integration of science and mathematics into engineering, and the role feedback can play in supporting integration. Both Janice and George initially elaborated on their earlier responses. Janice suggesting "front-loading," and George suggesting student "self-feedback." As in the previous excerpt, Alexa adopted an active facilitation strategy that pushed the team to think about writing the curriculum in a way that makes the things they talk about explicit and visible to other teachers who might use their curriculum. Prompted by Alexa's suggestion, the team began to brainstorm ways to "front-load" the curriculum, including making the time frame for activities explicit, explaining check-in instructions, and identification of questioning strategies that could be used to provide feedback. Critical Incident 20 also provides a concrete instance of how the team responded to the active facilitation by connecting their ideas to the curriculum redesign process. When Janice asks, "*Do we put that somewhere in our curriculum?"* it represents a shift in the conversation, and instantiates the seed of an idea -- Alexa's suggestion that it could take different forms, scaffold supports or notes to teachers -- ultimately led to improvising the curriculum. The idea of notes to teachers was manifested in the curriculum as *Teacher Tips for Setting up* *the Unit*. Tables 4.7 and 4.8 allow for comparison of the original *Teacher Background* notes with the final curriculum's *Teacher Tips for Setting up the Unit.*

Table 4.7. *Original Powered by Renewable Energy Curriculum's Teacher Background*

Teacher Background
● Teacher will consider student IEP/ESL/ special needs when forming groups. ● The teacher will need to have the *Kidwind* supply kit and also will have identified the variables students will test. ● Teacher will need to set up wind, solar, and water stations ahead of time for students. ● Teachers need to know that a big misconception occurs between renewable and recyclable.

Table 4.8. *Final Powered by Renewable Energy Curriculum Instructional Tips for*

Teacher Tips for Setting up the Unit
● The Client Letter ● Roles ● Modeling Good Teamwork ● Considerations for Differentiation ○ Use of Visuals and Repetition of Vocabulary ○ Writing ○ Grouping *First, we grouped students by gender. Fourth and fifth grade students in our STEM classes seem more comfortable expressing ideas with group members of the same gender. We also considered the cultural norms of our many Muslim students and understood that, in some cultures, boys and girls are separated and do not feel as comfortable working together.*

Next, we considered the many different abilities of our students as we grouped them. We placed similar achievement levels together so as to try and limit the tendency of one student overpowering the other members during decision-making or discussions. We felt this also made it less likely that one student would sit back and not participate because he/she thought the other group members would do all of the work.
Finally, we placed students who might need extra support in groups with lower- proficiency (or "New-to-Country") ESL students so that they would receive the extra teacher support available in our co-teaching model.

- Grouping

Throughout the unit, students will be working together in groups of three or four. Teachers will need to find a way to assign each student in the group one of four colors. This color will correspond to one of four engineering Roles (see attachments). Each member's color and role will change throughout the duration of the unit, and groups of three will need to rotate each member having two roles. (A colored sticker on a chair, table spot or t-shirt would work).

The original curriculum's *Teacher Background* notes was included in some, not all, of the unit's lessons (contact author for full curriculum). These notes consisted of short statements of things teachers needed to know or do, without elaboration upon how to do it. For example, "Teacher will consider student IEP/ESL/ special needs when forming groups" only states that IEP (special education) and ESL (English language learners) needs should be considered in grouping decisions. The notes did not state what considerations should be made, nor where to find information about it. Conversely, the final curriculum's *Instructional Tips for Teachers* had an extensive section of teacher tips in addition to teacher background notes for lessons within the unit. In Figure 4.19, I have shown one category, grouping considerations, verbatim from the final curriculum and reduced the other categories to a list of bullet points included in the final curriculum for the sake of saving space (for the full Instructional Tips for Teachers contact the author).

The teacher notes and instructional tips provide a specific example of how the

Thinking Through a Task session in general, and the facilitator role specifically, supported improvisations to the PbRE curriculum. For Team PbRE, one of the outcomes of the *Thinking Through a Task* protocol session was the suggestion for "scaffolding" various aspects of their curriculum for other teachers by including "notes for teachers" as to how to do it, which demonstrates how the teachers improvised the curriculum. The critical incident, combined with how the conversation led to improvisations of the curriculum, illustrates how the facilitator must strike a balance between supporting the ideas and expertise of teachers and pushing them to shift their thinking about curriculum for their classroom toward thinking about curriculum for other teachers.

The critical incident also demarcates a shift in the resources the teachers drew upon from their classroom to a perspective that is more in line with thinking of curriculum design for others. When Alexa pushed the team to think about how to make their classroom practice explicit in the curriculum it triggers a new strategy, one that encouraged the teachers to think about providing feedback as a means to let other teachers know what they did and how they did it.

The tendency for teachers to default to curriculum design for their own classroom use was a recurring issue for this team. On the one hand, teachers are not typically trained as curriculum designers for others (Huizinga et al., 2014). Even though teachers regularly engage in design activity while interpreting curriculum resources for their classroom setting, and tapping into personal and curricular resources to adapt, improvise and offload curriculum materials (Brown & Edelson, 2003). During the *Looking at Student Work* sessions, the teachers were engaged in an iterative process of developing, testing, and evaluating their curriculum for their classroom. As a result, it is not surprising that the team defaulted to consideration of what works for their teaching context. On the other hand, throughout the professional development and group coaching sessions, the teachers have developed considerable knowledge and expertise that they can share with other teachers. Given their training with *EngrTEAMS*, and their work over the course of the school year honing and refining their integrated STEM curriculum, they have the expertise and pedagogical content knowledge necessary to make the transition to curriculum designers. The *Thinking Through a Task* protocol initiated aspects of the curriculum design, but the facilitator played an important role in both supporting and pushing teachers to translate their experiences into curriculum that other teachers can use.

Summary of Team PbRE Looking at Student Work and Thinking Through a Task

Analysis of case 2 generated insights into both the role protocols play in affording collaboration and refinement of STEM curriculum, and how a combination of non-directive and directive facilitation strategies mediates teachers moving beyond curriculum design for their own classrooms and to consider the use of their STEM curriculum by other teachers. It also demonstrated the power of combining iterative evaluation of student work with iterative design of integrated STEM assessments and scoring rubrics. Finally, It showed how over the course of the process of curriculum redesign, the teachers adopted several lenses for the work. Whereas they initially approached the design of integrated STEM curriculum by drawing heavily upon the summer PD, across time they integrated what they learned from implementing the curriculum. Gradually, their ideas shifted both in focus and in content, which eventually made its way to the collaborative conversations and to the redesigned curriculum.

The integrated STEM curriculum started out as one thing and became something different. Similarly, the resources they drew upon started out as one thing and became something completely different – not only did their repertoire expand, the nature of the resources began to change. Each time they came to the *Looking at Student Work* and *Thinking Through a Task* session they learned something new or noticed something they did not notice before. Across time their new ideas and knowledge about assessment led to evolution of their interpretation and ability to design STEM assessments. Eventually, their new ideas, abilities and resources related to assessment trickled into the other lessons in the Powered by Renewable Energy curriculum. These are evidence of STEM PDC development.

Narrative Description of Case 3

In this section, I provide a narrative description from Team LSS followed by an in-depth analysis of their examination of student work and curriculum redesign sessions. First, I provide an overview of the team co-developed curriculum. Second, I share how each team participant described their classroom practices. Third, I explain how each participant described their curriculum. Fourth, I provide an analysis of Team LSS's *Looking at Student Work* protocol-guided sessions. Fifth, I provide an analysis of the team's *Thinking Through a Task* protocol-guided curriculum redesign session. Finally, I provide a summary of findings aligned with the study's research questions.

Team LSS Co-Developed Curriculum: Physical Science -- Light

In this seven-lesson unit, students were told that they have been hired to design a laser security system to protect the artifacts in a museum exhibit. A letter from the fictitious client outlined the criteria and constraints of the laser security design challenge and students participated in a series of investigations about the properties of light, including reflection, refraction, absorption, and transmission, to inform their designs. Students designed, tested, and improved prototypes of their security system. Figure 4.9 provides an overview of the unit, and a short summary of each lesson as written in the final curriculum follows.

Table 4.9. *Summary of Laser Security System Curriculum by Lesson*

Engineering Design Challenge: design a laser security system				
Lesson 1	**Lesson 2**	**Lesson 3**	**Lesson 4**	**Lesson 5**
Introduction to Engineering Design Process (1 day)	Reflection, Refraction and Diffraction (1 day)	Lenses, Absorption, Transmission and Reflection (1 day)	Mirrors, Reflection and Measuring Angles (1 day)	Light, Pass It On (leveled readers) (1 day)
Lesson 6	**Lesson 7**	**Resources**		
Engineering Design Challenge (1 day)	Summative Assessment (1 day)	Team Packet Rubric Target Practice Student Readiness Lesson		

Lesson 1: Introduction to Engineering Design Process: Students receive a client letter that introduces them to the context of their engineering design challenge, and complete a card sort activity to build their knowledge of the Engineering Design Process (EDP).

Lesson 2: Reflection, Refraction and Diffraction: Students are introduced to the properties of light by investigating why light from a flashlight differs from light from a laser and discuss the relationships between the wave properties and the color of light.

Lesson 3: Lenses, Absorption, Transmission, and Reflection: Students explore some of the basic properties of light by observing that light travels in a straight line and interacts differently with different surfaces.

Lesson 4: Mirrors, Reflection and Measuring Angles: This lesson builds upon students' understanding of reflection and refraction of light. Through hands-on activities, students observe light as it interacts with mirrors and lenses, and learn that light behaves differently depending on the medium with which it is interacting. Students measure and record the in-coming angle and reflected angle to explore how mirrors and lenses can be used to create a laser security system.

Lesson 5: Light, Pass It On (leveled readers): Students read background information on reflection, refraction, absorption, and transmission to enhance their understanding of science concepts and connect this to the EDP.

Lesson 6: Engineering Design Challenge: In this series of lessons, students work on the engineering design challenge by creating a model of a laser security system to protect the Science Museum of Minnesota (fictitious client). Students apply their knowledge of light to meet the criteria and constraints outlined in the client letter.

Lesson 7: Summative Assessment: This lesson serves as an assessment of students' knowledge of reflection and refraction. Students measure angles and drawing diagrams using math skills to display their understanding of science concepts.

Context for Team LSS *Looking at Student Work* Session

The three members of Team LSS are middle school teachers and have a secondary license in physical science. The team members work in the same district, and all three work in inner city schools with high levels of free-and-reduced lunch rates, wide ranging cultural, linguistic, and racial diversity. A distinctive feature of this team is that all of the teachers reported significant building-wide student behavior issues. As such, their classroom practices and curriculum use during implementation share a degree of attention to behavior management that is embedded in virtually everything they do.

In the following section I will build upon my discussion by delving deeper into the ways in which Team LSS drew upon curricular and personal resources to offload, adapt, and improvise their co-developed curriculum, and how the *Looking at Student Work* sessions, as well as deviations from the planned sessions, contributed to development of their STEM PDC.

Analysis: Team LSS *Looking at Student Work* Sessions

The descriptions above summarize how the participants described their curriculum implementation, and establish context for the analysis. In the following, I provide more information about Robert and Mark's *Looking at Student Work* sessions, beginning with how they described their implementation. For Amanda, I only include a description of how she described her implementation. I do not include an analysis of

Amanda's full *Looking at Student Work* session because neither Mark nor Robert showed up to her session as planned (one was sick, and something unexpected came up for the other one). Since the team is the unit of analysis, it does not make sense to include an analysis of the session when two of the three team members did not participate. I will, however, use some relevant information from that session where appropriate to inform decisions that arose in the other two sessions. The analysis is structured around a series of assertions, supported with critical incidents that inform the assertions.

Robert's Looking at Student Work Session

In the first *Looking at Student Work* session for Team LSS, Robert had brought several team student work packets, which served both as a guide for students and as the summative assessment for the laser security system design challenge. The packet was 13 pages long and included worksheets for each lesson within the unit, a teamwork "rubric," and a claim-evidence-reasoning writing task (see Appendix for the full curriculum). The team had not created their own rubric, rather they used an IB Middle Years Programme (MYP) rubric, since Mark and Robert worked in IB schools. The team used the IB Science rubric, Criterion A: Knowledge and Understanding (see Appendix D).

How Robert Described His Implementation

The *Looking at Student Work* protocol prescribes that the session begins with the presenting teacher providing a summary of their implementation, followed by identification of what students need to know and be able to do for success, scoring of student work, culminating in discussion and reflection. Following the guidelines, Robert described his implementation, emphasizing his implementation goals, the student packets, and the “testing station” he had built for students to test their designs. He also emphasized his goals for the challenge included having the appropriate structure so students needed to think through their design ahead of time, rather than just “tinkering” with the lenses, prisms and mirrors until they got their security system to work.

The packet served as the final product as well as a script outlining procedures for the design challenge. Students worked through the packet, which included a space for student to sketch a design of their laser security system prototype ideas. After choosing the prototype that would serve as their final prototype, they calculated its cost using a list of costs supplied to them for each prototyping material. Finally, students figured out the angles where the mirrors or the lasers would be placed, and tested their designs at the “testing station” (see Figure 4.8).

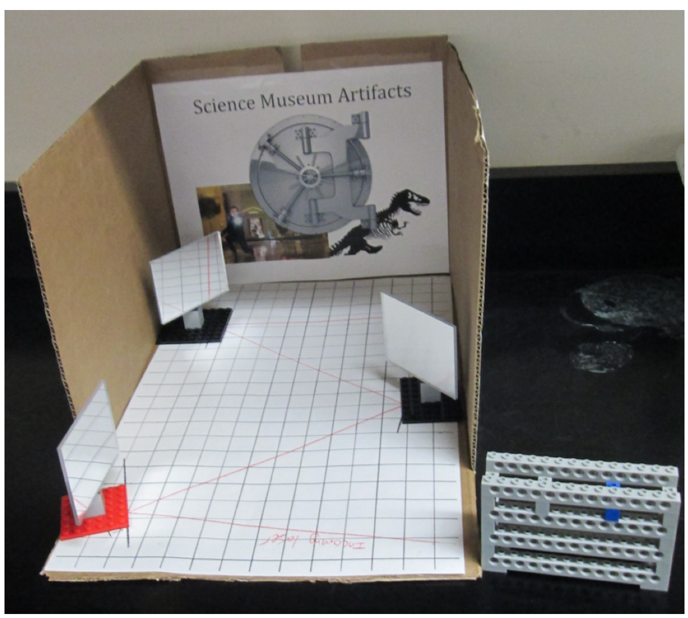


Figure 4.8. This figure shows the Laser Security System testing station students used to test their prototypes.

As previously mentioned, the *Looking at Student Work* protocol is divided into 7 segments; (i) presenting teacher introduction, (ii) grounding the work in what students need to know and do for success, (iii) examination of student work, (iv) individual scoring of the student work, (v) discussion of scoring decisions, (vi) feedback and reflection, and (vii) next steps. The facilitator was responsible for keeping the team moving through the protocol prompts and ensuring the discussion focused on examination of student work rather than what they observed in the process of teaching. However, given the fact that neither the protocol nor the IB rubric was not intended to score a packet of worksheets, this proved challenging.

Critical Incident Analysis

Three main assertions were drawn from the analysis of Team LSS's *Looking at Student Work* sessions. In the following section, each assertion is presented and supported with critical incidents that are representative of the ideas that arose during the sessions. The following critical incident took place during the first *Looking at Student Work* session, as the team transitioned from Robert providing context for the student work he had brought, to individually scoring student work with the IB scoring rubric.

Assertion 14

Teachers' beliefs about assessment for student learning constrain collaboration and refinement of the curriculum.

Critical Incident 17

JAYD: *The problem is we won't know if they [laser designs] worked but that's okay, because we can't take the time to try them out. That would take too long.*

ALEXA: *But then that's useful information when you're assessing work, because* *that informs—*

MARK: *Ya, that's something we can bring up that we didn't know.*

JAYD: *Unless they really drew it correctly, because I remember, we were tweaking away to make it work. So, what they drew may not be exactly what they did.*

MARK: *But I might even argue that it doesn't matter if it worked in the end, because they may have learned more than the group that—*

ROBERT: *It's about the process.*

MARK: *May have learned more than the group that got it to work. So it's not always about the final product, it's about how they got there.*

AMANDA: *Because we're always trying to teach them in engineering that, we don't care if they fail. Well, it's not that we don't care if they fail (all talking at the same time) —*

In this excerpt, the teachers and their team's coach, were beginning to score the student packets with the laser security system prototype drawings that Robert had brought to the team's first *Looking at Student Work* session. Jayd, the team coach, points out that the packet prototype drawings did not accurately reflect the "tweaks" student teams made after the preliminary prototype drawings were made. Jayd's concern triggered an impromptu discussion about the value of having student work for assessment, and reveals the team's underlying goals and beliefs about the role of summative assessment in student learning.

Mark argued that having final student work does not matter, "because they may have learned more . . .” Inherent in this statement is the belief that the prototype is not an accurate reflection of student learning. Robert supports Mark’s point, adding that what is important is, “the process.” Inherent in this point is the belief that learning comes about through participation in learning activities, which in this case, the is creating a laser security system prototype. Amanda supports Mark and Roberts’ points, adding that “in engineering . . . we don’t care if they fail.” Inherent in this point is a misapplication of something that was taught during the summer PD -- the value of embracing failure. The idea of embracing failure during the engineering design process is based upon the idea that when students engage in authentic engineering design tasks, their perceptions of “failure” may shift as they begin to see “failure” as an opportunity to learn why the prototype does not work and consider more functional designs (Householder & Hailey, 2012). When Amanda uses the concept of embracing failure to justify the lack of accuracy in the prototype drawings as unimportant, she is ignoring another aspect of “failure” that is critical for shifting students’ perceptions -- the iterative nature of the engineering design process. It is in the process of making multiple prototype iterations that students begin to see ways to improve functionality of their prototype designs that changes their perceptions of what it means to “fail.”

First, the team’s response suggests the team does not see the value of deep analysis of student artifacts to inform summative assessment development. The team’s response potentially undermines the *Looking at Student Work* protocol because the protocol depends upon a mindset on the part of participants -- that they endeavor to use student work to inform their instructional efforts (McDonald et al., 2024). If the team believes (knows) going into the session that the student work does not reflect student learning -- student understanding of the concepts teachers intend for them to learn -- then the value for informing instruction is reduced. Second, the response ignores the mismatch between using a scoring rubric to score a student work packet. Ignoring the mismatch between using a scoring rubric to score a student work packet creates a professional learning context that misses an opportunity to discuss how to improve the ways they designed the packet and used it. More importantly, the team never discussed the bigger picture -- how to more effectively create summative assessments that reflect student learning during the engineering design process and how that learning is (or is not) reflected in the summative assessment. Third, the response misses an opportunity to improve Amanda's implementation by redesigning assessment tools. The team missed an important opportunity to improve Amanda's implementation by redesigning the assessment tools their LSS unit ascribes to classroom instruction and to the summative assessment. Rather than discussing how to improve the quality of the final product, and "testing" it during Amanda's implementation with the goal of evaluating it during her post-implementation *Looking at Student Work* session, Amanda also used the packet as her summative assessment. Not surprisingly, the results were similarly inaccurate reflections of student learning.

The team's response to Jayd's concern provides insight into their team's goals and beliefs about student learning, assessment and their relationship to student work. As such, provides insight into development of the team's STEM PDC. Recall that the Design Capacity Enactment (DCE) framework posits that interactions between curricular resources (domain representation, object representation, and task representation) and teacher resources (teacher goals and beliefs, pedagogical content knowledge, and subject matter knowledge) drive teachers' curriculum use. Jayd had identified an inherent problem Team LSS faced for scoring the student work that presented an opportunity to inform the curricular resources the team used for assessment and, ultimately, the curriculum redesign. The team responded by justifying the problem, essentially saying it does not matter if the student work is accurate because the prototype does not reflect what was learned (Mark), the learning is in the process (Robert) and in teaching engineering design challenges we do not care about failure (Amanda). Thus, Critical Incident 20 illustrates several ways the teachers' beliefs about the value of assessment for student learning influenced their participation in the protocol-guided process. This opening sequence of their first *Looking at Student Work* session foreshadows a recurring issue of how to assess integrated STEM design challenges. At this point, the team is aware that the student work packets fall short of demonstrating prototype accuracy, but they proceed anyway. Thus, what could be construed as teacher disengagement with the protocol process is due to their underlying belief that student work does not reflect student learning. Their goals and beliefs serve as personal resources, which they draw upon to inform instructional consideration, and their beliefs that influenced the way they engaged in examination of student artifacts.

The following excerpt took place as the team was discussing how they had individually scored "Team B's" student work packet.

Assertion 15

The *Looking at Student Work* protocol mediates close analysis of student artifacts that supports teachers' ability to understand student learning.

Critical Incident 18

JAYD: *Well, light can be reflected by a mirror, refracted and reflected. So, they knew three things about light. It seemed like they knew, I kind of decided that they knew the angle of reflection here. The, angle of reflection is equal to the angle of incidence.*

ALEXA: *What's the evidence of that?*

JAYD: *So, they say they point a laser, the way it's going to reflect at the same angle. So, they know that the angle, it's going to be the equal angle. So they knew the Law of Reflection because they said the same angle. I mean, it's not stated the greatest but I think I am interpreting that they understand that concept, and that refraction bends light. That is true.*

ALEXA: *And then, so what is the rest of it here? I can't even read it.*

JAYD: *So they state, you can make a maze with it. "You can trick and change the glass to make it [light] bend more." So, it's not stated the greatest but, I mean, they showed that.*

ALEXA: *Okay, so what about, "apply scientific knowledge and understanding to solve a problem?"*

JAYD: *Well, they did show this, but then they didn't, this is incomplete here, but I figured they did this part here so I was kind of. So, I went to there, where is this?*

ALEXA: *How do you know they were using scientific information to solve a* *problem here? What is the evidence for that?*

JAYD: *Well, this is just the rough draft of three different ideas so, they have, well, these are mirrors and this is a prism here, and this is the laser.*

ALEXA: *You need to explain it to me, because I don't understand this science. I'm not questioning your judgment. I found it really hard to score these because I don't know the science well enough.*

JAYD: *Oh, okay . . . So look, they know about diffraction. I don't know, maybe, kind of. I don't know it's not very nice but--*

MARK: *I actually saw that in a different way.*

ROBERT: *The biggest issue with this one, in my opinion, was the fact that they did not show the laser beam actually coming in. At least it wasn't clear. I mean, this was sort of the one, but it goes through a lens and it doesn't refract. This goes through a lens, or goes through the mirror in their prototype. So it's not quite where it should be. Like, there's a little misunderstanding there. If those are the lasers they're going through a mirror (laughing).*

JAYD: *Okay, I'm thinking this shows that they're bouncing off this mirror. I mean, it's not great. It wasn't like a 7-8 [score], but it's showing kind of, I don't know where their other piece is but . . . I think that, maybe I was kind of trying to hurry up.*

ALEXA: *It's okay, that's fine. What about you Amanda?*

AMANDA*: I put it in the 3-4 [score range] because I felt like there was some recall in that first page [draws upon definition students wrote], which is stating* *like reflection and refraction. But I really didn't get a sense that they were able to apply it with the drawings, and not completing any evidence of the EDP they didn't complete the engineering design process.*

ROBERT: *That's what I put, they were at a 3-4, because they showed that they had the knowledge, but then I put minus for the process. They didn't necessarily understand the engineering design process, and that was reflected because they didn't finish it. There's no evidence that they actually chose one of those.*

AMANDA: *Right. There's just no evidence once you get past there.*

In this excerpt, the teachers, their coach and the facilitator, are comparing how they had individually scored the prototype drawings for "Team B." The scores were wide ranging: Amanda scored it as a 3-4; Robert scored it as 1-2 but "leaning to 3-4;" Mark scored it as 3-4; Jayd scored it at the 5-6 level; and Alexa scored it as at a level 2. The team discussed what counted as evidence in the student work, how it aligned with the rubric criteria, and whether or not Team B had accurately applied their understanding of reflection and refraction to solve the design challenge.

One of the premises of the *Looking at Student Work* protocol is that it calibrates scoring decisions by engaging in close analysis of student work (McDonald et al., 2014), and careful attention to evidence within the student work aligned with predetermined scoring criteria is an integral component of the process. This excerpt illustrates how discussion of wide-ranging differences in the student work can lead to deepened understanding of student learning. The event is one of many where the teachers have significantly different interpretations of the same student work -- that is, if they were grading the student work, different teachers would give the same work very different grades. At this point, the team has surfaced several ways the student work is ambiguous. The students had not shown the laser beam in the prototype, which left evaluation of student learning open to interpretation. It was also unclear if the objects were lenses, mirrors or prisms, which means it is hard to interpret student understanding -- that is, did they misunderstand or were they simply careless in how they drew their prototype designs? Despite the ambiguity of evidence in student work, the conversation does illuminate how the team engaged in close analysis of student work. The teachers' understanding of student learning developed through analysis and discussion, even when student ideas are not expressed "the greatest" (Jayd), the team was able to hone in on what information present in the student work informed their understanding and the "little misunderstanding[s]" of the students (Robert). Through identifying and articulating what each participant had noticed and counted as evidence, the teachers were able to calibrate their understanding of the students' capacity to "apply it [reflection, refraction] to the drawings" (Amanda).

The individual teachers' differing interpretations have important implications for assessment generally that do not get taken up during the conversation, but foreshadow future conversations. Namely, if student work is considered to be a proxy for student learning, then the conversation that ensued about evidence within the student work and how to interpret it has important implications for assessment and the curriculum redesign. In the following assertion and supporting critical incident, the team reflects upon the implications for the curriculum.

The following critical incident took place as the team was responding to the protocol prompt asking them to identify next steps, and provides further support for how the protocol mediated analysis of student work in a manner that supports the team's growing understanding of student learning related to STEM curriculum. Prior to this critical incident, as Robert had identified a problem with the curriculum that was raised once again as the team discussed their next steps.

Critical Incident 19

ALEXA: *So, next steps?*

ROBERT: *Um, I talked to Jayd about this. I do think that the weakest part in this project is refraction. Um, cuz we wanted to hit that piece of knowledge and it's not really reflected in the data that we just collected.*

ALEXA: *So, what would you want them to know that they didn't' know?*

ROBERT: *I think that, essentially to meet the state standard they just have to know what it is, right? I feel like this is formative assessment now. So it's just, to me, talking to the kids and stuff. So, I really feel like I had to do a lot of prodding to remind them what refraction was because reflection was so cemented. Like, when we did the practice with the lasers and the powder and stuff . . . we saw the laser beam, and they were like, 'Oh!' And they could visually see it. And we did the same thing with refraction. They got to see it go through the prism and see it bend, but for some reason it's not sticking the same. I think part of it is because it's not backed with the math. It's not backed with the project as strongly . . . If you noticed, almost all of them are like mirror, mirror, mirror, and then . . .*

they're not really worrying about refraction.

ALEXA: *So, how would you change this? Cuz, Amanda, you're starting now [implementing], right? You were writing, earlier, some ideas on changing the lesson. Any ideas?*

MARK: *Is it something worth even going through to get them to know that?*

ROBERT: *That's sort of where I'm at.*

MARK: *They don't need to know, like to get lasers to split into multiple beams.*

JAYD: *It's cool.*

MARK: *It's cool. It shows a pretty high understanding of things, but the amount of time that it would take, I don't know.*

ROBERT: *And there's no math that goes into it that they can do. At this level there's no way (emphasis) that you can calculate! You know what I mean?*

AMANDA: *It's not appropriate.*

ROBERT*: It's NOT even appropriate! I don't know. I'm not a physicist, you know what I mean?*

JAYD: *It's like today we were doing the, he was doing measuring and using the prisms and the lenses. You could technically measure those angles. Like, the angle of incidence, and see what that angle of refraction is, and that is what you would need to do if you wanted to add refraction into this . . . I think the point is to just say like, 'hey! this diffracts light, that's really cool!' That there's something that's called diffraction that's going to make it into different colors. and they were saying, 'oh, you can see a rainbow.' So, that's a great thing. Then* *they can see that, 'oh, the lens will bend it.' Okay cuz the next unit they'll get a little more into detail about that.*

ROBERT: *When I talk about the eye I talk about how it bends [light], but --*

JAYD*: But as far as, getting into it, I don't even know. I think that was a physics class I took where you talk about Snell's Law. This is getting into way too much content for a 6th grader. You know what I'm saying? . . . I'm just saying it's not appropriate at this level.*

In this excerpt, the team had identified a problem with the curriculum -- students do not understand refraction, nor is it necessary for them to measure it in order to come up with a solution to the design challenge. The team had also articulated several reasons it did not need to be in the curriculum: (i) refraction to meet the state 6th grade science standards; (ii) getting students to the point of understanding the concept takes too much time, the mathematics is too hard; and (iii) the mathematics is probably not even developmentally appropriate for 6th grade.

The team had originally designed their curriculum with the intent of teaching the science concepts (absorption, transmission, reflection, refraction) and mathematics concepts (angles, measurement), then having students use those understandings to inform their security system prototypes. As it turned out, the way the teachers wrote the curriculum was more effective for integration of some science and mathematics into the engineering challenge than for others. Specifically, the teachers felt that students understand reflection, but struggled to understand refraction. Robert speculated that part of the reason was probably "*because it's not backed with the math.*" The students could just “tinker.” As Robert said earlier in the protocol session, “have the lasers go bew, bew, beew! And just put this [prism] at the end, which most of them did.”

At this point, the team recognized that refraction was the concept the students had the most trouble with, and got around it by placing the prism(s) which would have required them to measure refraction at the end of the series of lenses and mirrors. The team also believed they understood the reason students struggled with refraction had to do with, “the way we had the question.” Despite the team’s concerns about their ability to actually integrate the science and mathematics, the team did not significantly re-design the lesson. Thus, the decision to offload the diffraction lesson -- to assign agency to the original curriculum and not modify it to reflect their concerns -- is not due to lack of content knowledge. In this excerpt, the team refers to Snell’s Law, the mathematics associated with diffraction, and how to technically measure the angles. Knowledge for STEM, they have science knowledge, they have the EDP knowledge, but the engineering design does not require use of refraction, nor is it in 6th grade standards. Nonetheless, they keep trying to make it fit. PDC is about recognizing AND mobilizing resources. They have these pieces that tell them and 2 x 2 = 4, yet they keep trying to interpret it as 2 x 2 = 8. In addition, in a segment of the transcript not included here, the team discussed the specialized equipment needs to make integrating the mathematics and science. Yet, *Lesson # 2: Reflection, Refraction and Diffraction,* remained virtually unchanged.

The use of the protocol for *Looking at Student Work* worked as intended, mediating reflection that helped to surface the problem with the co-developed curriculum. At this point, I am confident that the teachers have the subject matter knowledge, and the pedagogical content knowledge necessary to make the curricular modifications to have adapted the co-curriculum and ensured the LSS curriculum was doable, and had a productive learning sequence. Despite the content knowledge necessary to recognize the problem, the team did not act to either drop diffraction or make productive changes to the lesson. Instead, they offloaded the STEM curriculum, assigning agency to the original curriculum rather than making modifications to refine it. In the following, I build upon the assertions by analysis of Mark's protocol-guided session.

Mark's Looking at Student Work Session

Mark's was the final session for the team. In planning for Mark's *Looking at Student Work* session, I drew upon Robert and Amanda's sessions, as well as my experiences working with Team PbRE. Recall that Team PbRE had not brought a rubric to all three of our *Looking at Student Work* sessions and, to address the problem of not having a rubric with predetermined scoring criteria, I had been flexible with the *Looking at Student Work* protocol, designing a rubric on-the-spot. Collaboratively designing the rubric and subsequently using it to score student work had been productive for the team; as such, I made the decision to deviate from the protocol again. The rationale behind this decision was two-fold. First, I felt it was necessary to address the issue of having a common rubric for both the *Looking at Student Work* session as well for the summative assessment in the final curriculum. Second, I also wanted to honor the professional judgement of the teachers and use the curricular tools they had developed.

When Mark described his implementation he emphasized things he had changed, such as adding a teamwork rubric, a "target practice" mini design challenge, several technology-oriented pieces, and removing the claims-evidence-reasoning page of the packet. He also pointed out how, despite having co-developed the curriculum, each team member adapted and/or improvised the original co-developed curriculum. One thing he said sums up this point: “It’s kind of crazy to see how different we taught it even though we created it together, and then right off the bat, we’re just, (makes exploding gesture with arms) dramatically individualizing it. But that’s what teaching is (team laughing).”

While most of the team packet focused on procedures for students to follow (record team name, record steps of the EDP, etc.), one of the pages in the team packet was a science writing task, which utilized a claims-evidence-reasoning (CER) structure (McNeill & Krajcik, 2011). The CER focused on communicating understanding of how their prototypes met criteria and constraints, required them to cite evidence of having met the design challenge criteria, and support their ideas with reasoning as to how the prototype presented a solution to the LSS design challenge. The open-ended nature of the CER lent itself to scoring with a rubric, so I planned to suggest that we co-develop a rubric specific to the CER writing task they had included in the student team packet (see Figure 4.24). Thus, rather than trying to evaluate and score everything students did, the focus would be on one aspect of what the team wanted students to demonstrate their understanding of for the design challenge.

Despite my plan to make a rubric, which could be used to score the CER component of the packet, Mark’s *Looking at Student Work* session did not go as planned. The following assertions and associated critical incidents took place during Mark’s *Looking at Student Work* session.

Assertion 16

Interactions between classroom-level and curriculum level design activity requires creative facilitation strategies.

Critical Incident 20

The following excerpt took place at the beginning of Mark's protocol-guided session when Alexa, looking through the packet of student work, realized that Mark had not had students complete the component of the packet that she had planned to use to design a rubric and examine student work during the session.

> ***ALEXA:*** *Okay, I had a plan for today that included the writing piece.*
>
> ***JAYD:*** *Oh no.*
>
> ***ALEXA:*** *I thought it was in every one, I didn't realize it was a separate one. Um, so we'll just go with this. We'll go with the original plan. So let's just kind of —*
>
> ***MARK:*** *It's kind of crazy to see how different we taught it, even though we created it together. Then, right off the bat, we're just (makes exploding gesture) Dramatically individualizing it! But that's what teaching is (team laughing)* . . .

In this excerpt, Team LSS had just sat down to the protocol-guided session when Alexa realized that Mark had not had students complete the CER page of the packet (see figure 4.10), which was to be the focus of the *Looking at Student Work* session. When Alexa shared that she had planned on using the CER page, Mark gave voice to beliefs about the nature of teaching that have come up in subtle ways in several contexts, by several teachers, over the course of the school year -- teachers will "dramatically individualize the co-developed curriculum because "that's what teaching is."

<table>
<tr><td colspan="2">Claim: Our team's design should be chosen by the Science Museum of Minnesota because...</td></tr>
<tr><td colspan="2">Problem Constraints:</td></tr>
<tr><td colspan="2">Problem Criteria:</td></tr>
<tr><td>Solution:

Draw a labeled sketch of your model security system</td><td>Evidence:

Provide multiple pieces of evidence for why your design should be picked</td></tr>
<tr><td colspan="2">Reasoning:

Explain how your evidence (knowledge of light) influenced your design. Explain how the criteria and constraints were or were not met. Explain how your design best meets the needs of the client.</td></tr>
</table>

Figure 4.9. This figure This figure shows a worksheet from page 9 of the Laser Security System student packet, where students were asked to record a claim, support it with evidence, and articulate their reasoning.

Interactions between classroom-level and curriculum level design activity requires creative facilitation strategies. Beliefs about curriculum and the nature of teaching influence curriculum use (Brown, 2009; Brown & Edelson, 2003; Remillard, 2005) because they reflect what teachers value and, therefore, impact what they emphasize during instruction (Korthagen, 2009). In this case, Mark's beliefs also have implications for the *Looking at Student Work* session, and for productively informing the pending redesign of the curriculum. Prior to the session, Alexa had modified the protocol, with the intention of suggesting the team co-design a rubric for the CER portion of the packet, and use it to look at the student work specific to the CER, rather than scoring the entire packet. The suggested modification to the protocol was intended to address several issues that had arisen during Robert and Amanda's protocol-guided sessions: (i) develop a rubric a rubric all of the teachers on the team would use, regardless of their teaching context; (ii) ensure the final version of the LSS curriculum had a scoring rubric for the summative assessment; (iv) avoid evaluating the procedural components of the packet (that reflect teacher-driven ideas), and focus on an open-ended component of the packet that could be evaluated for student understanding; and (v) honor the team's ideas for a summative assessment task (rather than suggesting they scrap the packet and use the prototypes).

The use of the *Looking at Student Work* protocol during the post-implementation sessions was designed as an intervention to support teachers in the curriculum redesign process and promote development of STEM PDC in the process. The intervention depends on using student work that reflects students' understanding of how to use mathematics and/or science to solve an engineering design challenge. The packet was less a reflection of students' ideas, than it was a set of procedures for students to work through the design challenge, and a place to document each step in the process. In short, the *Looking at Student Work* protocol depends on a summative assessment that reflects student thinking about applying their learning over the course of the unit.

The protocol also depends on predetermined scoring criteria to frame the evaluation and discussion of student work. Recall from Chapter 2, that there is a "participatory relationship" between the curriculum and teacher practice (Remillard, 2005), whereby engaging teachers in design of curriculum serves to support professional growth because professional conversations serve as a tool for the development and refinement of ideas (McFadden & Roehrig, 2017). Through discussion of proposed ideas teachers work "inductively backwards" to structure their work, by linking the desired outcome to working principles (McFadden & Roehrig, 2017, p. 4). In this case, the discussion is a tool for teachers to develop, share, and refine their curricular ideas. The rubric defined the predetermined outcomes, and the protocol provided a set of working principles to facilitate the process.

Mark's decision not to have the students do the CER, and his subsequent observation, provide insights into the process of developing of STEM PDC. His belief that teaching is, by its nature a process of "dramatically individualizing" curriculum for teaching, is consistent with the goal of curriculum for his own classroom, which has been discussed in the previous analyses of the other teams' *Looking at Student Work* sessions. Rather than going into his implementation with the goal of using his implementation as a forum for testing the curriculum, he under-appreciated the potential benefits of the CER for informing his understanding of how students engage in writing scientific explanations within the context of a design-based STEM classroom. In the process, it was a missed opportunity for development of STEM PDC related to assessment in general, and writing in STEM specifically.

For Team LSS, the packet served as a resource for the curriculum on multiple levels. For students, the packet served as a step-by-step set of procedures for what to do and the order in which to do it, for the engineering design challenge. For teachers, the packet served as a script, a written manifestation of their instruction to reinforce their instructions to students. For the curriculum, the packet doubled as a summative assessment. Recall that summative assessment takes place after instruction with the purpose of determining what students know, to provide information about what has been learned and inform effectiveness of instruction. To serve as both a script/set of procedures (curricular resource) as well as an evaluative tool is inherently problematic in that step-by-step procedures are closed-ended, whereas the products of design-based engineering challenges are intended to represent open-ended solutions to problems/issues. In the following, I will elaborate upon these ideas, and shift my focus to the curriculum redesign process facilitated by the *Thinking Through a Task* protocol.

Team LSS *Thinking Through a Task* Session Analysis

The following assertions and supporting critical incidents took place in preparation for rewriting the curriculum, during the *Thinking Through a Task* session.

Assertion 17

As Teachers draw upon their personal resources to address perceived weaknesses in the curriculum and share solutions through storytelling.

Critical Incident 21

The following excerpt took place early in the *Thinking Through a Task* session, as the team discussed in-process supports for students.

> ***JAYD:*** *(talking to Mark) I liked when you had them go around and hit targets.*
>
> ***MARK:*** *Ya, that was probably the best part of the whole unit. I taped targets on popsicle sticks and then, at their table pods, I gave them easy challenges working up to harder challenges.*
>
> ***ROBERT:*** *Um hm.*
>
> ***AMANDA:*** *Cool.*
>
> ***MARK:*** *I have the targets, and they all had their hands on them.*
>
> ***ALEXA:*** *Was that in the original curriculum? (team shakes heads no).*
>
> ***ROBERT:*** *Was that part of the engineering design challenge? Or part of the previous lessons?*
>
> ***MARK:*** *Prior. It was right after we went through safety with lasers. Then I was like, this is going to make me see if you can actually use a laser.*
>
> ***ROBERT:*** *I feel like we all modified the pre-lessons quite a bit. But the actual design challenge, we didn't change it too much (team nodding heads yes). We only did a few little modifications but there was not, like, brand new stuff.*
>
> ***ALEXA:*** *So, why don't we just take a minute to get at some of those modifications on paper, because I feel like what you're talking about is really important and we haven't really talked about it in our previous meetings. A couple things have come up, but, why don't you just take a few minutes to list things that you specifically modified that were useful for the challenge, like your target practice thing.*

MARK: *That's what I'll call it.*

ALEXA: *That's what you called it?*

MARK: *Well that's what I will call it now. They basically did exactly what they had to do for the design challenge (laughing). Just holding mirrors in their hands and had a target at the end. It honestly worked better than the design process because they were all like, everyone had to have their hands going at the same time. It was exciting. And I dusted everything with baby powder.*

In this excerpt, the teachers and their coach, were responding to the protocol prompt, when Jayd, the team's coach, brings up an improvisation that Mark had made to the co-developed curriculum during his implementation.

The event is one of many that shows how the teachers drew upon their personal resources to anticipate the need to scaffold the design challenge. In the case of Mark's popsicle stick target practice, he knows what he wants the students to do to create a laser security system, but, drawing upon his personal knowledge that the students struggle to understand refraction, and knowledge of his students' academic skills, he anticipates the students do will not have the prerequisite knowledge and understanding to know how to use a laser and successfully complete the design challenge. Mark has determined that the students need more work with lasers to use them safely and effectively. During the earlier *Looking at Student Work* session, the team was in agreement that students need to understand for reflection and refraction, yet students seemed to understand reflection, but not refraction.

Mark came up with the idea of having a mini-design challenge prior to the students building their laser security system prototypes, an improvisation to the curriculum to address his concerns. In the process, he developed what he considers to be, "probably the best part of the whole unit," to work from easy challenges to progressively more challenging target practice. This allowed him to create a hands-on, engaging activity for students to practice using lasers. From the *Thinking Through a Task* session excerpt, it is clear that the team is intrigued, and open to each other's ideas for modifications to the "pre-lessons." Mark's mini-design challenge ended up in the final curriculum as the "Final Target Practice Student Readiness Lesson," as pre-lesson to Lesson 7: Summative Assessment. Below are the design challenges.

By improvising the curriculum with this "pre-lesson," Mark provided a preview for both himself and his students, supporting their ability to be successful during the design challenge. During the protocol-guided discussion, he said the students basically did what they had to do for the design challenge, suggesting an explanation for why he improvised the co-developed curriculum -- to provide structure for the engineering design challenge, moving systematically from least to most complex, and create an opportunity for students to use the materials. This is part of the recurring issue of the teachers' use of curriculum for their own classroom versus curriculum for other teachers. In this case, how much structure to provide for the engineering design challenge. The following assertion and critical incidents delve deeper into the issue of individual curricular modifications of the co-developed curriculum.

Assertion 18

Parallel storytelling serves as a mediating tool to deepen understanding of student learning and STEM curriculum.

Critical Incident 22

ALEXA: *So let's talk about those modifications. Let's finish the conversation about yours first. So, you talked about what you did and you said it was the best thing you ever did (everyone laughs).*

MARK: *Well, it was one of the best (team laughing).*

ALEXA: *Well, maybe not ever!*

MARK: *As far as the student engagement piece, everybody was super happy and really into it, and wanted to succeed in this. So, they basically made a human size grid and a target at the end. So I had them add another mirror, and add another mirror for each challenge. Then they knew, the next challenge is to do this, then they had, at the end, to add a prism, which threw things off a little bit.*

ROBERT: *I did something very similar to that and it's super engaging. It's a circuit building. So like most of them have built circuits in elementary school, not any more in St. Paul, (laughter). But, what I do is have four challenges and they want to do it. I mean, it's crazy. If you just keep challenging them and keep upping the game, you know what I mean? I mean, it's a game for them. I don't know, it's hard to tell how much actual learning is happening. Do you know what I mean?*

MARK: *Ya.*

In this excerpt, there are two distinct events. There is the “narrated event” (Wortham, 2001), which is the *Thinking Through a Task* protocol-guided discussion about modifications the teachers made to the co-developed curriculum. In this case, Mark described how he scaffolded the co-developed laser security system design challenge, adding a “pre-lesson,” which was a series of mini-challenges, each getting progressively more challenging. The improvisations he made to the LSS design challenge addressed the problem the team had identified during their *Looking at Student Work* session. Namely, students did not have to understand refraction in order to successfully design a laser security system prototype. In essence he added a discrepant component to the fourth challenge -- instead of reflecting off of a mirror at predictable angles (angle of incidence being equal to the angle of reflection) as reflecting light off of mirrors, light is refracted by the prism at different angles.

A storytelling event refers to the interactional context within which a speaker utters something (Wortham, 2001), whereby people craft ideas into a coherent story (Rymes & Wortham, 2011). As people tell their stories, they also “perform” them in the conversation (Rymes & Wortham, 2011, p. 39). These performance moments are analogous to storytelling events. When stories are performed, speech is used to bring past events to bear on what is taking place in the present as a way of understanding (Maybin, 2008). Thus, storytelling can be a powerful tool for understanding teaching and learning (Rymes & Stanton, 2011).

In this excerpt, when Robert evoked his circuit challenge, representing it is analogous to Mark’s popsicle stick target practice, the storytelling -- the sharing classroom experiences -- is an important way of attending to elements of good STEM science instruction. By re-enacting classroom experiences through their storytelling they constructed a performance of their words and, in the process, drew upon the classroom and each other as resources to more fully understand questions related to curriculum design. Robert positioned himself with Mark, validating the engagement factor of mini-design challenges in general. “I did something very similar to that and it’s super engaging.” He then proceeded to raise the broader philosophical question of learning, calling into question the value of mini-design challenges for learning. He did this by characterizing mini-design challenges as games. “. . . it’s crazy. If you just keep challenging them and keep upping the game, you know what I mean? I mean, it’s a game for them. I don’t know, it’s hard to tell how much actual learning is happening.” Positioning himself with Mark through storytelling, he was able to raise a concern about the value of mini-design challenges for learning, because he is calling into question his own past instructional choices.

What started as a conversation about modifications to the original curriculum had taken a reflective turn. When Robert observes that, “it’s crazy . . . it’s hard to tell how much actual learning is happening,” he is raising the issue of the curriculum and learning outcomes for students -- what is the nature of learning? He is also intrinsically drawing a distinction between integrated engineering design challenges (LSS challenge) and mini-design challenges (popsicle stick target challenge). In doing so, he inherently characterized the Engineering Design Process and “learning” and the mini-engineering design process as a "game." At this point, Mark and Robert are taking on the issue of how does one know when students are learning and when they are just playing a game.

The following critical incident took place immediately following the previous one, and provides further support for the assertion that storytelling mediates development of STEM PDC.

Critical Incident 23

ROBERT: *I mean, you can tell that they're learning. I'm not saying that they weren't learning by doing that. They are, but it's just hard to document it, and know that they're learning. Does that make sense?*

MARK: *Ya.*

ALEXA: *A little, but what's --*

MARK: *The assessment piece is purely like you observing them.*

ROBERT: *It's formative. It's just like okay, watching them do it. I'm not saying we shouldn't do it; I'm just saying, refining it would be hard because it's just play. You're letting them play.*

ALEXA: *Which is okay.*

ROBERT: *It's good.*

MARK: *It is good. And there wasn't any pre-planning. It was all just on the spot. Like, as far as the engineering piece, to get better at that and foreshadow things, and then actually have to follow somebody else's rules to be accepted, that's a whole new ball game.*

ROBERT: *Yup.*

ALEXA: *So how did, it's sounding to me like you're saying it was more than just engagement. It was productive, somehow, but it is hard to identify?*

ROBERT: *Um hm. Hard to quantify the p r o d u c t i v e n e s s (enunciating each sound) of it. Whenever you let kids play it's hard to quantify it.*

ALEXA: *So what unit, what lesson did you do that in (referring to Mark) and what lesson did you do that in (referring to Robert).*

ROBERT: *I didn't do it; it was just an example of something I do that is very similar where you keep upping the challenges.*

ALEXA: *Gotha.*

MARK: *Do you start with like two wires and a battery?*

ROBERT: *Two wires, a battery and a light.*

MARK: *And then you keep taking a piece at a time?*

ROBERT: *Okay, so what I do is, I say, 'okay come up and get your stuff for challenge 2.' It's like a switch and a wire and they have to turn the light on and off. I think the hardest one, and no one gets it ever, is like a double switch. No, I do the double switch where they have to have two lights. Then they have the double, I don't know if they're called butterfly switches or whatever. I call them mad scientist switches. One turns on, the other one turns on, and then the really hard one is where they have two separate switches. I don't know, I'd have to look it up, but it's essentially creating two separate circuits with one set of batteries. Like, one of the challenges is they have to make the light brighter. Then I give* *them another battery. So, they have to put the batteries in series to get the light brighter.*

MARK: *Um, I want to say, it was one of my last lessons where I put it before the engineering design process. Because it was the whole, lasers can hurt your eye, I made it sound like your head would blow off if you touched anybody's face! I was like really serious about all that stuff, fooling around. They still had fun but they demonstrated their ability. So, a big part of it was the safety aspect. But another one is how they think they can kind of have the mirror just kind of there, and it will go where they're thinking that it's going to go, and like one degree change with their, if their hands are moving a little bit. So they knew to steady them on the table or something. I think that was, maybe that took away a lot of that needing to tinker so much? After the fact. But I don't know.*

ALEXA: *So, what do you guys think? How does that make it productive?*

AMANDA: *It's more practice. I think it decreases the tinkering in the actual engineering challenge because the mirrors are a very tinkery thing.*

ROBERT: *I think letting the kids play with the materials, especially before a larger project like this, is beneficial even if there is no technical "learning" (gesturing with finger quotes) going on. You're teaching them how to manage the materials correctly. And that's what you were getting at, right?*

MARK: *Um hm, right. And then it turned into like, 'hey I can actually get a few things out of this!' Instead of they can't do this! They can't do that!*

ALEXA: *So are you thinking you would add this in the redesign.*

ROBERT: *I think it would be beneficial. Because when we're doing the redesign it is sort of like these are optional things, right? Because you need to have a relatively cooperative group of students. And the nice part too, is that by doing that part, you can tell if the students are cooperative or not. So you can shut it down then instead of shutting it down mid-engineering design process.*

MARK: *Yup.*

AMANDA: *Nodding, um hm.*

In this excerpt, the issue of learning versus game play shifts to assessment when Robert says, ". . . you can tell that they're learning . . . but it's just hard to document it . . ." Earlier Robert positioned himself with Mark through storytelling about the circuit challenge. In this excerpt, Mark positions himself with Robert by supporting Robert's assertion that it's hard to document, "The assessment piece is purely you observing them," which Robert then labelled as formative assessment. There is a sense of reciprocity to their storytelling as their evolving understanding of Mark's improvisations to the curriculum are discussed in terms of learning versus game playing, and how to assess the efficacy of their instruction and curriculum.

The discussion also depends upon storytelling -- evoking personal experiences to inform their thinking -- and co-construct meaning. As Mark and Robert engage with curricular ideas during the *Thinking Through a Task* protocol-guided session, they drew upon their collective personal resources to rethink what it means to learn during engineering design challenges, and how to assess learning within their lessons.

As Mark and Robert negotiate the meaning-making process, the rest of the team is also a participant, listening and taking in the ideas. At this point, because “It’s just play,” refining the curriculum “would be hard,” due to the assessment piece being formative. Robert’s contention is essentially: play plus formative assessment equals hard to refine the curriculum to include the target practice challenge. This contention is interesting for several reasons. On the one hand, taken literally, assessment of the mini-design challenge could be difficult to assess. The activity is hands-on, open-ended, and has multiple levels. On the other hand, so does the laser security challenge. At this point the team’s thinking is still unresolved, and they have not yet addressed the larger issue that their current assessment (the packet) does not effectively capture student learning either. For one thing, it is a team packet, and does not reflect individual learning. The packet is also not an accurate reflection of the final prototypes students built. In addition, the packet was not completed at the end of the learning cycle, as is typically the case with summative assessments, so one could argue that it is also a formative assessment.

Finally, Alexa intercedes, rephrasing the conversation and inviting clarification when she suggests it sounded like more than engagement, that it was productive, but hard to identify. This triggers a continuation of the circuit storytelling event, with Robert providing more details, to which Mark argues that students had fun, but they also “had to demonstrate their ability,” which he felt reduced the need for tinkering. In essence, Mark is addressing the earlier problem with the design challenge, the students are forced to think more deeply about refraction, “how they [students] think they can kind of have the mirror just kind of there, and it [laser light] will go where they're thinking that it's going to go, and like one degree change with their, if their hands are moving a little bit."

Storytelling served as a way to draw upon each other as resource. Through sharing classroom experiences the teachers drew upon each other as resources for curriculum redesign. The teachers paid attention to elements of good STEM instruction, which surfaced through storytelling. A component of their storytelling was that it helped this collaborative team to provide more specificity about how the curriculum and how it was enacted -- how they experienced it, how they perceived their students experienced it, and what strategies they used. These performance moments are important for teachers' PDC development because they provide a way for them to work through challenging aspects of classroom implementation and curriculum design. The excerpt illustrates how meaning is layered and used by teachers to grapple with a challenging aspect of curriculum. By referencing and characterizing classroom events, in this case mini-design challenges, they speak to the present curriculum design task.

Collectively, these excerpts describe how teachers used storytelling moments to inform curriculum redesign and to develop STEM PDC. As they embodied and enacted classroom experiences, they drew upon each other as resources to understand good STEM instruction, and took away new skills and understanding. Drawing upon each other as resources is a new category of PDC I refer to as drawing upon collective resources. (note: make stronger point -- important if proposing new category to PDC lit.)

Comparison of Team LSS *Looking at Student Work* and *Thinking Through a Task*

Analysis of the critical incidents related to the use of protocols for examining student work and redesigning curriculum for Team LSS provided insights into several aspects of redesigning of the co-developed curriculum and development of STEM PDC that addressed the research questions. Several aspects confirmed findings from the other two cases, such as storytelling, facilitation strategies and protocols supporting a focus on student learning. In addition, there is one area of distinction between the *Looking at Student Work* protocol and the *Thinking Through a Task* protocol – the opportunities the *Thinking Through a Task* protocol affords for pushing teachers from designing curriculum for themselves into the realm of thinking of curriculum for other teachers.

Concluding Thoughts from Individual Case Analysis

For all cases, integrated STEM curriculum started as one thing and became something different. The changes in the co-developed curriculum were evident in the curricular materials themselves between the original and final curriculum. The EDP became more structured. SEM integration became more integrated – more explicit and scaffolded connections between science and engineering and mathematics and engineering. The depth and extent of the changes varied across cases, but were present in all nonetheless.

The changes in the co-developed curriculum were also evident in the conversations the teacher design teams had during the protocol sessions. The changes took place through a predictable pattern of telling stories from the classroom during the protocol sessions, then using the insights gleaned to collaboratively refine their understanding of STEM curriculum and how to redesign it.

Similarly, the resources the teacher design teams drew upon to inform their evolving understanding and redesign efforts started as one thing and became something different. The resources changed in both depth and breadth. The changing resources and their interactions were sometimes implicit, their curricular or teacher resource origins evident to an outside observer only in the degree to which the design activities mimicked (or did not) the *EngrTEAMS* PD. For example, integrating whole lessons they participated in into their curriculum, or mimicking tools such as the client letter. In these cases, analysis of the data revealed change in PDC development through inference. In other words, the degree to which the team offloaded, adapted or improvised within the co-developed curriculum being a reflection of the degree to which they relied on the curricular resources learned from *EngrTEAMS*, and the degree to which they relied on their personal resources to co-develop the curriculum.

For example, two teams followed the lesson sequence used during the summer PD – introduce the EDP, teach content lessons for mathematics and science, and the culminating lesson being the engineering design challenge. One team began with the engineering design challenge before and content was taught, followed by teaching the content, and culminating in re-prototyping in the final engineering design challenge. In the first instance, analysis suggest two teams assigned greater agency to the PD in their initial design than the third team. This analysis would be related to scope and sequence of the unit, Thus speak to the Procedures component of the DCE Framework.

Other times, recognizing the changing resources and their interactions was explicit. As the teachers told stories from their classroom implementation of the co-developed curriculum, the stories were not all the same in terms of their role in supporting PDC development. Sometimes, the stories were anecdotal, relating to classroom events such as procedures or behavior. Other times, the stories triggered similar or related stories from others, functioning to build upon the ideas being conveyed to the team. These co-storytelling events functioned to co-construct meaning and insights about STEM curriculum and how to redesign it. Still other times, these co-storytelling events took on a nuance whereby co-construction of new understandings of STEM curriculum relied upon events outside of the *EngrTEAMS* program. In this variation of storytelling, the teacher that raised an issue had introduced a personal resource, whereas in the other two iterations of storytelling the resource was tethered to the co-developed curriculum. Thus, storytelling moments were helpful for the teacher design teams' PDC developing. The stories served as a collective resource to clarify and hone understanding.

Storytelling moments were also helpful analytically, often making visible the ways in which individual teachers had offloaded, adapted and improvised the original curriculum, indication individual PDC development through curricular and personal resources brought to classroom implementation. When shared with the team, the ideas were further refined (or not) they provided evidence of STEM PDC development. The teams often reinterpreted how they had written the EDP or their approach to SEM integration. In these cases, they inevitably discussed how to reconcile the new ideas and insights with the original curriculum. These were helpful analytically, but also when combined with what ultimately got written into the final curriculum, informed interpretation of both the "how" and "what" of STEM PDC development. Sometimes the teams *identified* new ideas, insights and understandings that reflected an expanded repertoire of resources, but the new knowledge did not get translated into the curriculum redesign. Other times, teams both *identified* and *mobilized* new ideas, insights and understandings of STEM curriculum. Thus, storytelling informed interpretation of differential PDC development – the ability to *identify* vs. the ability to *identify* and *mobilize* resources to craft instruction. Finally, all of this often took place within the context of creating and evaluating assessment.

In the next chapter, I present my cross-case synthesis. I have two goals for the cross-case synthesis: (i) to refine the major findings of individual case analysis; and (ii) to make theoretical generalizations about the findings as they related to the DCE framework.

Chapter 5 Cross-Case Synthesis

Because storytelling is such a common and powerful means to understand and relate to students and colleagues, as well as understand and take action oneself, narrative is critical to the practice of teaching (Rymes & Wortham, p. 38).

Organization of Cross-Case Synthesis

In chapter 5, I first briefly review the goals of this study and outline my cross-case analysis strategy. Second, I present a summary of the assertions generated from the data in chapter 4, organized by research question. Finally, I summarize the findings and discuss theoretical generalizations.

Rationale

Building upon the individual case analysis presented in chapter 4, in this chapter, I present a cross-case synthesis of the conceptual ideas and uses of STEM curriculum. Cross-case synthesis is an analysis strategy that embodies making a "new whole out of the parts" with the goal of generating unique concepts and interpretations of familiar issues (Cruzes et al., Introduction para. 5, 2015). Qualitative synthesis in case study research is necessary to build upon the body of knowledge generated from analysis of individual cases (Cruzes, Dybå, Runeson, & Höst, 2015). In this study, analysis of the three individual cases revealed 18 assertions, each supported by illustrative critical incidents. In this chapter, the assertions were synthesized, resulting in three meta-assertions that reflect patterns and themes across cases.

Goals and Analysis Strategies

The cross-case analysis that follows reflects an attempt to understand the relationship between teachers, curriculum design, and the resources teacher design teams drew upon for collaboration and refinement of their integrated STEM curriculum. The research questions guiding this study considered the nature of curricular modifications and the factors that influenced new understandings of STEM curriculum and STEM PDC development. For the cross-case analysis I focus on assessment, and the components of the *Framework for Quality K-12 Engineering Education* the teacher design teams chose to talk about -- integration of science, engineering and mathematics (SEM) and the engineering design process (EDP).

The topics of SEM and the EDP were not protocol-inspired decisions. Rather, the topics were driven by problems the TDTs' encountered during implementation and what they discussed during the protocol-guided sessions. I do not mean to imply the teams never discussed other aspects of the *Framework*, they did. However, the other aspects of integrated STEM were not persistent topics that kept coming up across cases. For a review of the *Framework for Quality K-12 Engineering* see Chapter 2.

Although the focus of this analysis was on PDC development during protocol-guided, not during classroom implementation, the classroom events were also relevant. When problems came up during the protocol-guided sessions, they were often used to inform the teacher design teams' understanding of STEM curriculum, and their decisions to offload, adapt or improvise the original curriculum.

Cross-Case Analysis Strategy

I followed a specific strategy to draw the individual case narratives together, allowing me to explore similarities and difference, and expose the overarching storylines across cases. First, I compiled a table of the assertions and supporting critical incidents from each case, organized by team and aligned by protocol intervention and research question. Next, I revisited the assertions, combing similar ones, revisiting the critical incidents that supported them when necessary. Finally, synthesized the patterns and themes to generate three meta-assertions.

Cross-Case Analysis of Team DIY, PbRE and LSS

This section is organized in the following manner: First, I present a summary of assertions from chapter 4, aligned with the research questions they address. Second, I state the meta-assertion that was generated from cross-case synthesis of the assertions. Third, I explore the implications of the major findings.

Table 5.1. *Summary of Assertions from Individual Case Analysis, Aligned with Research Questions and Used to Inform Meta-Assertion 1*

Research Questions	**Assertions**
How does the use of a protocol for examining student work afford and constrain collaboration and redesign of co-developed curriculum?	● The use of a protocol for examining student work makes classroom practice visible. ● Facilitation strategies afford collaboration and refinement of curriculum. ● Combining iterative design of assessment tools with and evaluation of student work, affords adaptations and improvisations to the STEM curriculum. ● Improvisations to STEM assessment mediate adaptations to other lessons within the STEM curriculum that inform STEM PDC development. ● Teachers' beliefs about assessment for student learning constrain collaboration and refinement of the curriculum during the process of examining student work. ● The *Looking at Student Work* protocol affords close analysis of

	student artifacts and supports teachers' ability to understand student learning. ● As Teachers draw upon their personal resources to address perceived weaknesses in the curriculum and share solutions through storytelling.
How does the use of a *Thinking Through a Task* protocol afford and constrain collaboration and redesign of co-developed curriculum?	● Facilitation creates opportunities to shift teachers' thinking about curriculum for their classroom towards curriculum for others, and serves as a resources for PDC development. ● The protocol surfaces different goals and values for assessment practices in their own classroom for assessment than they do for the co-developed curriculum. ● Directive facilitation strategies push the teams to move beyond thinking of curriculum design for their own classroom, and consider curriculum design for other teachers. ● Parallel storytelling serves as a mediating tool to deepen understanding of student learning and STEM curriculum.

Meta-Assertion 1: Protocol and Facilitation

The use of protocols to structure teacher design team conversations promotes a focus on student learning. Flexible facilitation strategies are necessary in order to move teams from curriculum design to curriculum development.

Cross-case synthesis related to Meta-Assertion 1 suggests protocols afford collaboration and refinement of STEM curriculum in two ways: using a combination of types of protocols (examination of student work, co-design of curriculum tools), and using a combination of *directive* and *non-directive* facilitation strategies. In turn, pedagogical design capacity develops through the protocols and facilitation as the teacher design teams learned about student learning.

Use of Protocols to Structure Teacher Design Teams

Protocol Collaborative Resources

Protocols are physical tools that mediate activity in specific ways, which is driven by the composition of the protocol. In this case, types of prompts they used and their focus on assessment promoted an emphasis on student learning. The *Looking at Student Work* protocol emphasized collaborative evaluation of curriculum artifacts (student work, rubric), whereas the *Thinking Through a Task* emphasized collaborative creation of curriculum tools. The combination of evaluating and redesigning assessment artifacts and the tools that were used to produce them, helped the teams focus on multiple aspects of student learning. The *Looking at Student Work* protocol explicitly targeted student understanding of content. The *Thinking Through a Task* protocol targeted the instructional goals and criteria to evaluate those goals. In other words, the use of protocols to structure teacher design team conversations promoted a focus on both student learning and instruction.

The protocols served as collaborative resources that focused the teacher design team conversations on student learning across all three cases, and was true no matter what the content area was. It did not matter if the topic of conversation was SEM integration, the EDP, or other curricular ideas that were less frequently raised, such as teamwork.

Value of focus on student learning. Besides the obvious value in focusing on student learning for understanding what students have learned, prioritizing student learning helps inform instructional practices (McDonald et al., 2013). Thus, an emphasis on student learning served dual purposes. First, a focus on student learning helped teachers to compare instructional practices with how effective they were to bring about the intended learning goals for students. Second value of a focus on student learning helped teachers notice opportunities for improving assignments and communicating expectations to students.

Combining Non-directive and Directive Facilitation Strategies

Facilitation Collaborative Resources

Cross-case synthesis related to Meta-Assertion 1 also suggests that the use of a combination of *non-directive* and *directive* facilitation strategies shifted teacher design teams from approaching curriculum design from the goal of designing for themselves, toward a goal of designing curriculum for other teachers' use. By *non-directive* I mean helping the team stay focused on the prompt, and using questioning strategies that served probed for explanation or elaboration to something someone else raised, but not introducing ideas or suggestions. By *directive*, I mean using questioning strategies that probe assumptions, direct the team's attention to ideas that they had not considered, and making suggestions.

Focus on shifting curriculum design perspectives. One of the premises of effective PD programs is that it should be embedded in teacher practice, which was the case for these teams – examination of student work from their classrooms that is the result of what they taught, and the curriculum they wrote. However, the ultimate goal of the *EngrTEAMS* PD program was to create an integrated STEM curriculum unit for any 4^{th}-8^{th} grade teacher interested in using it.

Curriculum design activity that teachers engage in as part of their day-to-day practice and curriculum development are related, but not analogous activities. Curriculum design activity refers to selecting, interpreting and implementing curriculum (Remillard, 2005). Curriculum development is more encompassing, and includes attending to coherence across lessons and curriculum evaluation strategies (Huizinga et al., 2014).

Non-directive facilitation strategies are normally the goal when using protocols for collaborative work. Non-directive strategies meet the participants where they are, because the goal is to help the team co-construct knowledge, not impart it. However, the use of directive facilitation strategies was helpful in this context for two reasons. One reason I've already discussed, teachers are simply more comfortable and experienced in the curriculum design arena. A second factor that constrained the teams from naturally moving into the curriculum development arena was the teacher design teams believed that they should leave certain things up to any future user of the curriculum. The use of directive approaches was useful for helping them realize that there was a great deal they had done in their classroom that would be useful for other teachers.

Value of shifting curriculum design perspectives. Using a combination of non-directive and directive facilitation strategies can leverage the different classroom-level and curriculum-level goals. Whereas non-directive strategies meet teachers where they are and honor teacher contributions to the curriculum design process, directive strategies can push teachers out of their comfort zones in productive ways. Directive facilitation served as a collaborative resource because it helped teachers to connect-the-dots between what they had done in their classroom and what was embodied in the curriculum. For example, one of the teams had made considerable improvisations to the original curriculum related to providing feedback to students during implementation, and during the protocol-guided sessions discussed the benefits to students to get them talking more and the exponential value for English Language Learners; yet, there was no mention of how to integrated their ideas about feedback into their curriculum. In this instance, directive facilitation served as a resource to raise awareness, instigate deepened thinking about the needs of teachers who had not been through the *EngrTEAMS* PD, and inspire collaboration about how to incorporate their ideas into the curriculum.

Across all three cases, the value for using a combination of non-directive and directive facilitation served as a resource that shifted teacher design teams' thinking from curriculum for themselves toward a more holistic view that considered curriculum for others. Another way of saying this is it helped shift the teams from curriculum design toward curriculum development. In the process of identifying and mobilizing resources, they honed their understanding of STEM curriculum and STEM PDC.

The protocols and facilitation strategies served as collaborative resources the teacher design teams drew upon to learn about student learning, and expand their curriculum development expertise. The collaborative resources interacted with the curricular resources and teacher resources they had available to them to inform their understanding of STEM curriculum and evolve their PDC – their ability to identify and mobilize resources to craft instruction. In the next section I present meta-assertion 2 and its implications.

Table 5.2. *Summary of Assertions from Individual Case Analysis, Aligned with Research Questions and Used to Inform Meta-Assertion 2*

Research Questions	**Assertions**
How does STEM PDC develop and evolve in teacher design teams while examining student work and redesign a co-developed STEM curriculum?	● Making classroom practice visible surfaces problems with the curriculum, solutions to them, and opportunities for improvement. ● Storytelling mediates development of STEM PDC. ● Variations in teacher's goals, beliefs and experiences influence decisions about curriculum use and redesign. ● Customizing the co-developed curriculum through improvisations in the classroom, refines understanding of STEM curriculum. ● Coming to understand STEM assessment serves as a collaborative tool that mediates STEM PDC development. ● Collaborative design of assessment tools facilitates development of STEM PDC. ● Improvisations to STEM assessment mediate adaptations to other lessons within the curriculum that inform STEM PDC development. ● Interactions between classroom-level and curriculum level design activity requires creative facilitation strategies. ● Beliefs about the individualized nature of teaching constrains collaborative curriculum development. ● Teachers draw on personal resources to address problems with the curriculum during implementation, and share problems and solutions to problems with teacher design teams through storytelling. ● Parallel storytelling serves as a mediating tool to deepen understanding of student learning and STEM curriculum.

Meta-Assertion 2: Resource Interactions and STEM PDC Development

Teacher design teams draw upon a combination of curricular, teacher and collaborative resources to co-construct and evolve their understanding of STEM curriculum. In turn, as teachers engage in curriculum redesign their STEM PDC expands and develops.

Interactions of curricular, teacher and collaborative resources. The teacher design teams often encountered tensions between emulating what they had learned during the *EngrTEAMS* PD and written into their co-developed STEM curriculum, and what they found to be possible in their classrooms. They used the protocol-guided sessions to explore and reconcile those tensions. In the process, they considered their students' interests and abilities, their own capacity to manage materials, their understanding of the content EDP, SEM, and assessment, and their understanding of integrated STEM curriculum. All of these factors played roles in the teams' decisions to offload, adapt and improvise the co-developed curriculum.

Making adaptations and improvisations to the curriculum required complex design activity interpreting, selecting, reconciling, accommodating and modifying the original and reimagined curriculum. In doing so, curricular, teacher and collaborative resources available to the team morphed, expanding into new resources available to the team to craft instruction. The collaborative understanding the teams arrived at, based on classroom-level modifications the individual teachers made during implementation, were often different than either the original curriculum or the modifications made during implementation and presented to the group. In these instances, the teams needed to reconcile, accommodate and further modify the new ideas with the original curriculum. Curriculum material changes between the original to the classroom resulted in one set of curricular, teacher and collaborative resources. Curriculum material changes made between the individual modifications to protocol-level modifications resulted in another set of curricular, teacher and collaborative resources. The cross-case synthesis suggests the decisions to adapt or improvise the curriculum, resulted in different teacher-curriculum interactions and different trajectories of STEM PDC than decisions to offload.

Teacher-Curriculum Interaction Trajectories and PDC

Trajectories of STEM PDC Development

Cross-case synthesis related to Meta-Assertion 2 suggests that curricular, teacher, and collaborative resource interactions during collaboration and refinement of STEM curriculum result in STEM PDC development along two possible trajectories: Trajectory 1 resulted in adaptations and improvisations to the original STEM curriculum. Trajectory 2 resulted in offloads to the original STEM curriculum.

For trajectory 1, PDC can be characterized as *recognizing* and *mobilizing* resources to redesign the curriculum. This process was influenced by resource interactions as the teams used classroom-level insights and attempted to (re)interpret, (re)select, reconcile, accommodate and (re)modify their STEM curriculum. For trajectory 2, PDC can be characterized as *recognizing*, but not *mobilizing* resources to redesign the curriculum. This process was also influenced by resource interactions as the teams used insights to (re)integration, (re)selection, reconciliation, accommodation. However, the process did not include (re)modification of STEM curriculum. It should be noted, that not modifying the curriculum did not necessarily mean the team was not capable of making modifications they chose not to make. Rather, I did not have evidence to inform the why so I cannot speak to it.

In my discussion of meta-assertion 1, I discussed protocols and protocol facilitation strategies in terms of how they promoted a focus on student learning, and in terms of moving teams from the curriculum design to curriculum development arenas. In my discussion of meta-assertion 2, I addressed how decisions to offload resulted in different trajectories of PDC development than did decisions to adapt or improvise did.

Before preceding to a discussion of meta-assertion 3, it is useful discuss the role assessment played. Because it was often in the context of assessment that these PDC-related themes emerged, for a complete understanding of the cross-case synthesis findings.

Assessment 'of' and 'for' integrated STEM curriculum

Assessment '*of'* and '*for'* learning (Gibbs, 1994) is a phrase originally used to make a distinction between assessment whose purpose is evaluating what has been learnt (assessment *of* learning), and assessment whose purpose is to inform and improve the learning process (*for* learning) (McDowell, Sambell & Davison, 2009). I borrow this phrasing to describe how a combination of multiple iterations of evaluation and co-design of curricular artifacts related to assessment afforded collaboration and refinement of STEM curriculum and STEM PDC development.

Assessment as a collaborative resource for STEM PDC. Assessment often served as a focal point of PDC development because, in this study, it lived at the intersection of co-creating and co-evaluating curricular artifacts and curricular tools. This multifaceted approach to collaborative work engaged the teacher design teams in multiple opportunities to deepen their understanding of the nature of STEM assessment and led to the identification of two complementary conceptions of STEM assessment: Assessment 'of' and 'for' STEM curriculum.

Evolving understanding of STEM curriculum. The type of student work the teacher design teams brought to the protocol-guided sessions triggered the different trajectories I discussed earlier. These processes called upon the teacher design teams to interact with curricular, teacher and collaborative resources in distinct ways.

When the teams brought student-created prototypes, the conversation emphasized evaluation of assessment criteria and how completely the student work reflected it.

Using rubrics to score student work during the was a process of evaluating student learning, reflecting on what students understood about the EDP, their ability to apply mathematics and science to build a prototype that met the criteria and constraints outlined in the engineering design challenge. This process aligned with assessment *of* learning.

Co-creating scoring rubrics was a process of calibrating the stated learning objectives with assessment criteria. The purpose was to ensure continuity of what was taught with expectations for the assignment and make improvements to the assignments, the assessments, and make sure integration goals were met. That is, to ensure assignments captured all three content area standards (science, engineering, mathematics) were written into the assignment. This process aligned with assessment *for* learning.

For the teams that went through both evaluation and co-design of assessment and assessment tools, the role assessment tools played changed throughout the process. Initially, assessment served as a curricular resource, a physical tool within the curriculum, the teams drew upon to plan and implement the engineering design challenge. With co-creating the scoring rubric, assessment shifted away from being a curricular resource physically embodied within the curriculum. Co-creating the scoring rubric began as ideas on a piece of chart paper, guided by their interpretation and understanding of STEM curriculum (SEM, EDP) and the content standards and skills that informed their learning objectives. This was a fundamentally collaborative process, drawing on the interpretation and understanding of each teacher participant and compiling their entirety on the chart paper for group consideration.

Value of combining ‘of’ and ‘for’ assessment design activities. Collectively, the assessments were virtually absent from the original curriculum because the teams’ initial understanding of STEM curriculum reflected what they had learned during the summer STEM PD. Since assessment was not emphasized, when the teams developed their assessments they did not give full consideration to the topic and the curricular tools that might be necessary for other teachers -- or even themselves -- to use the curriculum. As one team put it when discussing their struggles with understanding STEM assessment:

We didn’t approach it [piloting the engineering design challenge] from how are we going to grade it . . . Which was too bad none of us were like, ‘we should practice grading this right now.’ With the summer pilot, we didn’t think about how are we going to grade these [prototypes], because we weren’t assigned grades. Here are these kids, they built these things, then off we went. I mean, we didn’t quite take full advantage of those opportunities when they came up . . . (Kurt, Team DIY).

The creation of assessments and assessment tools during implementation reflected individual teachers’ ideas and approaches to assessment. Creation of assessments and assessment tools during the protocol-guided sessions reflected collective ideas and approaches to assessment. Focusing on how the teams perceived and mobilized collaborative resources, curricular, and teacher resources illustrates how the process of collaborative design of the scoring rubric supported development of STEM PDC for these three cases. All three teams were in similar situations following their implementations of the curriculum because they learned new things about STEM curriculum, but the teams also recognized gaps in the student work and sought to figure out more effective ways to engage students in the engineering design process to avoid tinkering and ensure students apply science and mathematics to inform the design of their prototypes. All three teams initially approached filling the gaps by discussion about content integration effectiveness.

Team DIY stayed in this space, whereas the other two teams began a process of co-developing a scoring rubric for their assessment, which caused them to revisit their ideas about what they wanted students to know and do, and how they wanted students to engage with those ideas. Team PbRE and Team LSS drew more heavily upon collaborative resources than Team DIY did through collaborative co-design of assessment tools. In the end, Team DIY made only minor adaptations to their final curriculum that did not reflect the rich conversations they had. For example, in their conversations they constantly discussed the challenges and lack of authenticity of budget and identified more productive alternative. Despite this, they kept budget in the final curriculum and added the geometry of nets only as an extension activity rather than a core mathematics integration strategy. The team demonstrated their evolving STEM PDC, but they failed to reinvent their curriculum to its fullest potential. The recognized affordance, but failed to mobilize the resources to fully act upon them.

Conversely, the teams that moved beyond discussion and debate into co-design of scoring rubrics (and assessments) ultimately developed curriculum that reflected more productive designs of both STEM assessment and the other lessons within the STEM curriculum. For example, Team PbRE, who had instigated co-designing a rubric when they failed to bring one, reinvented every aspect of their curriculum -- the scoring guidelines, the assessments, the data collection lesson leading to the engineering design challenge, and the teacher background. The team demonstrated that they recognized assessment affordances within their curriculum, they were able to mobilize collaborative resources, in this case co-design of the scoring rubric to reinvent their curriculum and grow their STEM PDC. Interactions between curricular, teacher and collaborative resources resulted in higher quality STEM curriculum. Integration was no longer confined to the engineering design challenge as it had been in the original curriculum. Rather, the lessons leading to the design challenge established building blocks for integration and introduced the content relevant for the engineering design challenge.

Concurrent with this process of changing conceptions of assessment, was an evolving understanding of STEM curriculum in general. These changes were not instantaneous, they took place over time, and reflected a process where earlier ideas and versions of assessment served as resources for transformation into more sophisticated ideas. In addition, the changes did not happen randomly or in isolation, they evolved due to interactions between resources. Assessment of and for STEM curriculum served as a mediating factor for STEM PDC and is a significant finding in this study. In the end, assessment served several purposes, which fell under two broad categories. These activities can serve dual purposes, which can be described as assessment of STEM and assessment for STEM.

Table 5.3. *Summary of Assertions Generated from Individual Case Analysis and Aligned with Research Questions and Used to Inform Meta-Assertion 3*

Research Questions	Assertions
How does STEM PDC develop and evolve in teacher design teams while examining student work and redesign a co-developed STEM curriculum?	● Storytelling mediates development of STEM PDC. ● Facilitation strategies serve as resources for collaboration and STEM PDC development. ● Storytelling helps teachers connect classroom design activity to curriculum design activity by shifting their perspective from tasks for their classroom to curriculum development for others. ● Teachers draw on personal resources to address problems with the curriculum during implementation, and share problems and solutions to problems with teacher design teams through storytelling. ● Parallel storytelling serves as a mediating tool to deepen understanding of student learning and STEM curriculum. ● Collaborative design of assessment tools facilitates development of STEM PDC. ● Improvisations to STEM assessment mediate adaptations to other lessons within the curriculum that inform STEM PDC development.

Meta-Assertion 3: Storytelling and STEM PDC Development

Storytelling supports collective interpretation, selection, reconciliation, accommodation and modification of STEM curriculum. By sharing past experiences through storytelling, co-storytelling and parallel storytelling teachers drew on each other as resources for curriculum design.

Storytelling is a powerful tool for teaching and learning (Rymes & Wortham, 2011), because it serves as a way of performing ideas to bring about clarity and hone thinking (Wortham, 2001). In this study, storytelling served as a resource that brought together classroom-level experiences and curriculum-level design activity. In the process, initial ideas about STEM curriculum, and available resources became less classroom-specific, and more connected to desirable aspects of integrated STEM curriculum (SEM, EDP). As teacher design teams brought their individual experiences, challenges and problems to the group, they grew their understanding of STEM curriculum and expanded their repertoire of available resources.

Use of Storytelling to Inform Curriculum Design Activity

Types of Storytelling

Cross-case synthesis related to Meta-Assertion 3 showed storytelling can be about any number of things, some substantive and some not. In the case of stories not relevant to curriculum redesign, the stories often took a one-and-done function within the team conversations. For example, storytelling often took the form of concerns about classroom behavior or management that did not concern the other participants. In these instances, storytelling did not get translated into curriculum redesign activity.

Usually, co-storytelling and parallel storytelling kept coming up because they were about substantive issues that multiple participants weighed in on. When multiple teacher design team participants commented on the same topic, it introduced a diversity of ideas and opinions, and deepened insights. Co-storytelling often took on a elaborative function, where one participant built upon the ideas of another. For example, it a team member felt students understanding was not fully reflected in the student work, they often shared a story about an individual student to illustrate their point. This often triggered another participant to interject additional examples to support the statement. Parallel storytelling often took on a similar, but more expansive function, where one participant interjected additional ideas or contradictory evidence that was not specific to their STEM curriculum, but related. In chapter 4 I illustrated parallel storytelling with the example of two Team LSS participants parallel storytelling about a STEM Laser Target mini-challenge and an science Electric Circuits mini-challenge. Their stories worked in parallel to inform their musing about what it means to learn vs. play within the context of an engineering design challenge. Co-storytelling and, more often, parallel storytelling were also used to disagree. For example, when something worked in one participant's classroom and not in another's classroom. A familiar example from Chapter 4 was using budget criteria as the mathematics integration working for the 5th grade classroom but not the 2nd grade classroom.

Storytelling as Bridging Classroom and Curriculum Design Activity

Storytelling served as a way to make classroom-level design decisions visible, and allow those events to inform collaboration and redesign of the curriculum. When individual participants made their classroom events, practices and curricular modifications visible, they served as triggers for curricular, teacher and collaborative resource interactions. As the teacher design teams discussed and debated they bridged the classroom and curriculum redesign process by reinterpreting, their understanding of STEM curriculum. Often this led to re-selecting and re-modifying. If the team did go down this path, rather than reject the introduced ideas, then this required reconciling the original and new ideas about STEM curriculum, as well as accommodating the needs of all participants students and the abilities of the participants themselves.

Classroom-level interactions between teachers and the co-developed curriculum were reflected in individual decisions to offload, adapt or improvise the co-developed curriculum. When these decisions were made visible through the stories they told, the stories served as collaborative resources for the entire team and informed curriculum-level interactions. Curriculum-level interactions, during the protocol-guided sessions, reflected interactions between curricular, teacher and collaborative resources. Furthermore, these interactions resulted in expanding the resources available to the teacher design teams.

Whereas initial resources were comprised of teacher-curricular interactions, when classroom experiences were shared and considered, they became an additional set of resources that encompassed the original resources and the problems identified, adaptations and improvisations that attempted to solve the problems, and identification of unanticipated opportunities that inspired modifications to the curriculum. Thus, different types of stories elicited different types of interactions. Some built upon previous design decisions, some aimed at aligning new ideas with existing ideas. I alluded to this earlier with my "trajectory" of events. Storytelling is intimately related because it triggered the teacher design teams to revisit ideas and incorporate them, or reject them.

Value of storytelling as bridging tool for PDC. Storytelling served as a bridging tool between classroom and curriculum design activity by triggering resource transformation. As classroom-level and curriculum-level interactions took place, ideas became resources, then uncertainty became possibility, then possibility became new resources, and so on, as resources were transformed into new resources available to the teacher design team.

Bridging classroom and curriculum design brought focus to the five types of interactions Brown (2002, 2009) described in his dissertation, and later in his book chapter: interpretation, selection, reconciliation, accommodation, and modification. In his work he described their relationship to teacher design activity to demarcate the differing nature of design activity. In this study, stories bridged classroom-level and curriculum-level design and the result of that was often revisiting interpretation and selection of components of the STEM curriculum. Sometimes the outcome was to adapt or improvise, depending on team goals, knowledge and abilities. In these instances, modification of the curriculum elicited the need to reconcile and accommodate the original and new curriculum. Within this process, the teams evolved their understanding of STEM curriculum and their STEM PDC developed to reflect the new understandings and resources available to them.

Curriculum Development, Teacher Practice and STEM Reform

Last Thoughts about STEM Curriculum Development

In the *Framework for Quality K-12 Engineering Education,* SEM integration is defined as the application of science, mathematics, and engineering knowledge in a manner that emphasizes cross-disciplinary connections. For all three cases, SEM integration and the EDP were high priorities, and none of the teacher design teams felt they had gotten it completely right the first time. As a result, how science and mathematics were reflected within the student work and how the process of engineering a prototype that met criteria and constraints was a frequent topic of conversation. Despite they were happy with student motivation and engagement, the teams recognized that, in most cases, their students could have designed the prototype solutions without using the science and the mathematics they had taught.

In all cases, the teams did not satisfactorily resolve the issue of SEM integration the first time it came up, nor were they entirely happy with the time and materials management required to do multiple iterations of prototypes as prescribed by the EDP. When these topics arose, as they did again-and-again, they rarely talked about the problems and potential solutions without invoking experiences from their implementations. In applying the stories from their classrooms, their personal knowledge, skills and beliefs to the co-development of the STEM curriculum, the teams distributed their cognitive resources across each other, the curricular tools, and collaborative tools available to them.

Last Thoughts About Teacher practice

What teachers know, and how they use their knowledge is at the core of developing PDC (Brown, 2002, Brown & Edelson, 2003). Through the process of writing curriculum, implementing it, and participating in protocol-guided discussion, the teams honed their understanding of SEM integration and the EDP, and used their new knowledge to refine their STEM curriculum. Drawing upon the summer PD as a resource, the teams interpreted what they had learned and wrote their understandings of integrated STEM into the curriculum. During implementation they often found their initial ideas did not make sense for their students and/or the teaching. In these instances, the original curriculum was modified by the teachers, often becoming more structured. Across all three teams, it was the problematic components of their curriculum and solutions embodied in the adaptations and modifications that was highlighted and debated during the protocol-guided sessions. The teams came to the curriculum design process with an understanding of STEM curriculum from the resources they had been provided with, but there were several unanticipated issues that arose that did not work for their students. Their implementation informed their personal understanding of STEM curriculum within their teaching context, and the protocol-guided sessions became a space where they could share their experiences, hear the ideas (and experiences) of the other team members, and to clarify their understanding of SEM integration and how to assess it. By hearing what worked for others, what did not work, and about the adaptations and improvisations others made to the co-developed curriculum to address problems of practice and improve the curriculum, the teacher design teams were able to adjust their understanding of STEM and hone their STEM PDC.

Last Thoughts About STEM Reform

Up to this point, I have focused on similar patterns of PDC development across the teams. Qualitative cross-case synthesis is also concerned with gaining insights that can be gleaned due to variation in results and conclusions across cases (Cruzes et al., 2014). One significant difference in how the teacher design teams interpreted the EDP for STEM curriculum related to the task representation component of the DCE framework -- how they structured tasks for students. The teams infused the EDP with very different structures, which ranged from open-ended (Case 1), to semi-structured (Case 2), to highly-structured (Case 3). Similar to the SEM integration conversations, the EDP conversations revolved around problems they encountered, the adaptations and improvisations the teachers opted for to resolve the problems, and how to best use their new insights to redesign the STEM curriculum. In reconciling their new insights and accommodating the needs of their students for structure to support the EDP process, their STEM PDC development was closely connected to the EDP (task representation) structure, and how it evolved over the course of the study.

The engineering design process is inherently ill-structured (Householder & Hailey, 2012); yet, based on the ages of their students and their teaching context, each team infused the EDP with structure to guide the process. The manner in with the teams over-laid structure upon the EDP is relevant to STEM reform in general because structure of the curriculum influenced decisions to adapt and improvise the curriculum as the need arose. In general, adaptations and improvisations to the EDP were the result of the need to make the EDP more structured.

Case 1 originally designed the curriculum to begin and end with the engineering design challenge, teaching the content in between to support the second iteration. During the protocol-guided discussions the team debated the challenges to this sequencing decision, and the ways to impose structure while maintaining the spirit of the EDP. As Matthew pointed out, “Ill-structured is one thing. There has to be enough structure so that it just doesn’t turn into a complete disaster. It has to be structured enough would be one lesson I’ve learned.” The team never completely resolved this issue, due to the different ages of their students. Thus, the data suggests this team’s PDC development is best described as their ability to recognize issues related to task structure had evolved over the course of the post-implementation conversations, but there is no evidence to suggest they could mobilize the resources to satisfactorily fix the problem in a way that satisfied all team members.

Case 2 originally designed the curriculum imposing structure to the EDP through teamwork, by assigning roles to group members and having students participate in a mini-design challenge to practice their roles. During the protocol-guided sessions they frequently discussed how well this had worked and credited explicit attention to teamwork as an important factor in the success of their curriculum. They also felt it was one of the most important components of the STEM curriculum. As one of the team members said, “Our very first lesson of the year we did a job, and stickered the tables so they had jobs. Then we had like two rules. One was ‘no finger pointing,’ . . . Ya, we put a lot of emphasis on teamwork. Ya, it was like work as a team, it all just kind of clicked with me. We don’t really do that [before], but we always had these fights.” During the protocol sessions they built upon the structure further, discussing, and ultimately, improvising the data collection process as well making it more closely align with their SEM integration goals. Whereas initially they had students make their own table in their notebooks, they changed this, assigning predetermined variables for students to address during the EDP. The data for case 2 suggests this team’s PDC development is best described as adapting the EDP. Preserving the teamwork task structure but adding structure to help students collect data that would be useful later. Therefore, STEM PDC development related to task representation of the curricular resources was informed by by the post-implementation discussions.

Case 3 imposed a high degree of structure through the use of a student packet. The packet provided step-by-step instructions for students to work through the engineering design challenge. Imposing structure through procedures and scripts for students shifted through the post-implementation sessions as the participants sought to build more individual accountability into the STEM curriculum. Evidence from the protocol-guided sessions suggests that the team's PDC development was similar to that for case 2, through drawing upon collaboration, curricular and teacher resources, they adapted the EDP to ensure individual students must demonstrate their understanding of the EDP.

In summary, the "what" of STEM PDC development, during the protocol-guided sessions, was informed by individual adaptations and improvisations, but linked to the STEM curriculum by common experiences co-developing, implementing, evaluating and discussing STEM curriculum during the protocol-guided sessions. Through the protocol-discussions the teams uncovered problems with the original curriculum, discovered how different teachers resolved those problems, and sought ways to reconcile solutions and accommodate the needs of their students to improve the curriculum. Through distributing the knowledge and experiences across the team new iterations and ideas about STEM curriculum moved the teams past what they had initially learned during the summer PD and driving STEM PDC development.

As a result of the three-week summer PD, the teachers brought their initial understanding of curricular resources related to SEM and the EDP to the table, and drew upon their interpretation of them for implementation and redesign of the curriculum. In addition, the teachers brought personal resources to the table that they drew upon for implementation and redesign. The resources individual teachers drew upon reflected their interpretation of the *Framework for Quality K-12 Engineering Education* and personal resources they had developed over the years from their practice. Finally, the teachers drew upon each other as resources. As individual teachers shared their stories from implementation and the teacher design teams discussed how to accommodate those experiences with each other and with the STEM curriculum, their personal resources were transformed into collective resources through their shared experiences. Interactions between resources, resulted in their decisions to offload, adapt or improvise the original curriculum.

In the next section I will address theoretical generalizations that were generated from the data, its implications and possible avenues for future research.

Chapter 6 : Discussion, Implications and Future Research

Organization of the Chapter

Chapter 6 responds to the study's research questions by addressing the data presented and analyzed in Chapters 4 and 5. In these pages, I summarize the findings of this study and make connections to the results of previous studies. I also discuss implications for engaging teachers in design and development of STEM curriculum as a means of supporting development of STEM pedagogical design capacity.

The chapter is split into three sections, each connected to the study's major findings and relevant literature discussed in Chapter 2. First, the theoretical assertions developed in Chapters 4 and 5 are briefly reviewed. Second, I revisit the DCE framework in relation to the findings of this study. The last part of the chapter addresses potential future research on developing of STEM PDC, engaging teachers in design of STEM curriculum, and teacher professional development.

Discussion

This study explored the resources that influence STEM PDC development. Protocol-guided discussions were analyzed to understand how the resources they draw upon to craft instruction contribute to decisions to offload, adapt and improvise STEM curriculum. The data provided some insights into the relationship between curricular and personal resources described in the PDC and DCE literature. The findings illuminated interactions between a new resource not previously described -- collaborative resources --

and its influences on the teacher-curriculum relationship teachers forge as they engage in STEM curriculum design.

In this section, I discuss the implications for how these teacher design teams developed their STEM PDC development, and the role protocols play in affording and constraining it. In the DCE framework (see Figure 2.4 in chapter 2), the teacher resources category includes subject matter knowledge, pedagogical content knowledge, goals and beliefs. The curricular resources category includes domain representation, procedures, and physical object representation. In the model, resources were presented as tools teachers draw upon for curriculum design that determine decisions to offload, adapt or improvise with curriculum materials. PDC is a type of teacher resource (Beyer & Davis, 2013) that develops through teacher practice as they identify and mobilize resources and build their understanding and capacity to craft quality instruction. Recall from chapter 2 that Brown (2002, 2009) described the relationship between PDC and the DCE framework as the “what” and “how” of teacher practice. Data from examining the student work and curriculum redesign protocol-guided sessions led to several assertions that provided insights into successful collaboration and refinement of STEM curriculum and development of STEM PDC. These, in turn, led to reconceiving the DCE framework.

DCE Framework Reconceived: "What" and "How" of Collaborative Resources

Cross-case synthesis of the three contrasting cases in this study led to developing a modified version of the DCE Framework that includes a new category I call Collaborative Resources. I identify three classes of collaborative resources: assessment, storytelling, protocols and protocol facilitation. Assessment refers to both formative and summative assessments, and scoring rubrics that served as tools to define and communicate assessment criteria. Storytelling refers to the interactions that took place in response to the protocol prompts, as well as a strategy the participants used of invoking classroom experiences. The protocols refer to both the physical protocol, and facilitation strategies using them. Figure 6.1 provides a visual of the modified version of the Design Capacity Enactment Framework.

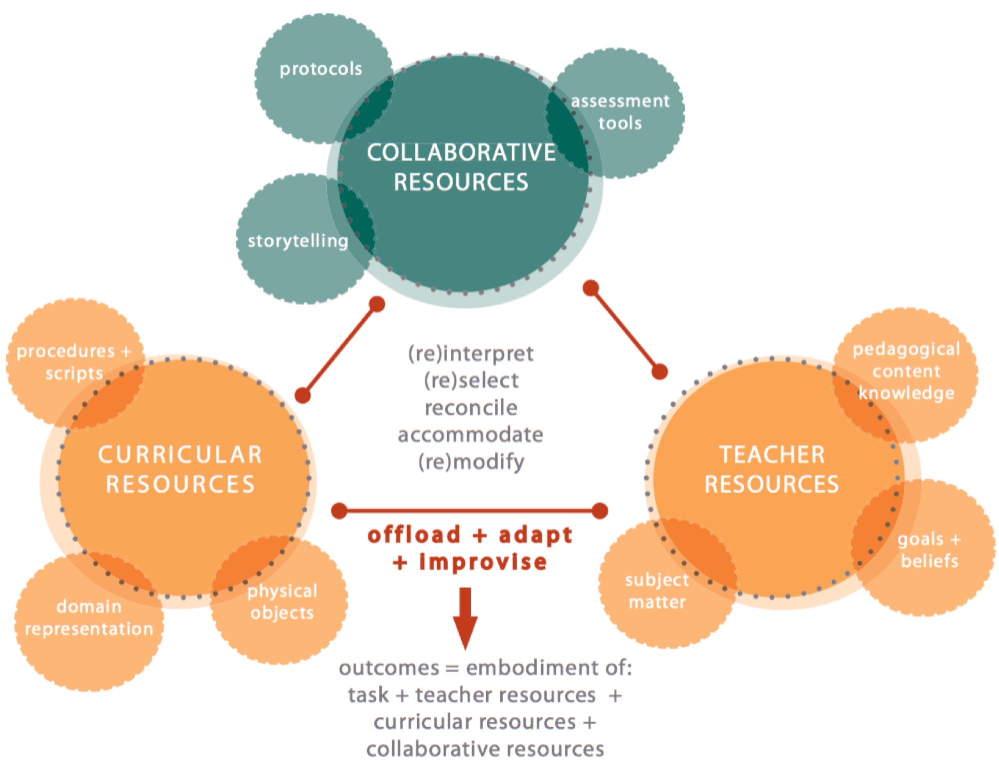


Figure 6.1. This figure shows the modified version of the Design Capacity Enactment Framework, which includes collaborative resources.

The "What" of Collaborative Resources: Protocols, Assessment and Storytelling

Collaborative resources refer to the ways in which the teacher design teams drew upon context-specific resources to evaluate student work and redesign curriculum, gain insights into STEM curriculum, and develop their STEM PDC. Recall from chapter 1 that I used the DCE framework in a new way and context. I applied it to curriculum development, rather than externally prepared curriculum. I also applied it to teacher design teams during protocol-guided sessions, rather than individual teachers' use in the classroom. Before discussing the new framework's implications for PDC development, and how I used it, I will define the subcategories of collaborative resources.

Protocol resources. *Protocol resources* refer to tools the teams utilized specific to the *Looking at Student Work* and *Thinking Through a Task* protocols. Protocol resources includes both physical resources (prompts) and intellectual resources (facilitation strategies). Similar to curricular resources, the protocols have multiple aspects of representations and function as resources the teams drew upon for offloading, adapting and improvising the curriculum, and their STEM PDC development. The protocol tools include physical, contextual and social resource representations. The physical tools include the prompts within the protocols, and associated built-in artificial constraints (time, role assignment). The contextual tools encompass the circumstances of their use (post-implementation, co-design of curricular tools, curriculum redesign). The social tools primarily refer to facilitation and participant interactions with each other.

Storytelling resources. *Storytelling resources* refer to a collaborative resource the teacher design teams used to bring together individual experiences and share experiences with the STEM curriculum. Storytelling took three forms: storytelling about classroom events (which encompassed a range of topics), co-storytelling (co-constructing meaning), and parallel storytelling (bringing related, but not STEM-specific ideas to bear on meaning-making).

Storytelling served as a resource by helping teachers to "perform" new insights and ideas. Through retelling and sharing their stories -- the problems that arose, their strategies for addressing problems, their experiences and student experiences -- the individual teachers made their classroom experiences visible to the group.

Assessment resources. *Assessment resources* refers to the ways the teachers used STEM assessment as a resource to focus and maintain focus on student learning. Assessment resources during the *Looking at Student Work* protocol-guided session emphasized evaluation of student work. Assessment during *Thinking Through a Task* protocol guided sessions emphasized co-creating assessments and assessment tools.

The "How" of Collaborative Resources: Teacher-Curriculum Interactions

The "how" of collaborative resources refers to PDC development, and how resources are identified and mobilized to offload, adapt and improvise curriculum materials for instruction. Within the original framework, the outcomes were described as "instructional outcomes: TASKS" (Brown & Edelson, 2003, p. 4), but not clearly defined. In the new framework, in addition to instructional tasks, I include they types of interactions Brown (2002, 2009) described and defined. My inclusion of interpretation, selection, reconciliation, accommodation and modification reflects my effort to make visible the fact that the types of interactions played an important role in decisions to offload, adapt or improvise, and the interactions between curricular, teacher and collaborative resources.

To demarcate between original resources and the expanded resources available to the teacher design teams, I integrated the five types of interactions in two places. I place them amongst the three types of resources, and as part of the outcomes to reflect their transformations. In addition, I represent interpretation, selection, reconciliation, accommodation and modification as: (re)interpretation, (re)selection, reconciliation, accommodation and (re)modification to acknowledge that the first iteration of the STEM curriculum took place before this study ensued. In this context, Representing the constructs with the prefix (re)- allows makes explicit the fact that the design teams were revisiting their design ideas, and reconciling and accommodating them for the first time.

Collaborative Resources: A New Construct for PDC Development

For this study, I make the distinction between curricular resources, teacher resources, and collaborative resources to distinguish between the curricular resources that afforded and constrained teacher activity, the resources teachers bring to bear on curriculum design and development, and the collaborative resources that are context-specific to post-implementation evaluation and redesign of STEM curriculum. In doing this, I follow Brown's (2002) definitions of curricular and teacher instruction resources. Curricular resources being physical representations (lesson plans, domain representations, etc.), and teacher resources being comprised of "intellectual" resources such as goals, knowledge and beliefs that shape teacher-curriculum interactions (Brown, 2002, p. 48). Like Brown, I acknowledge the artificial distinction, but use it for analytic purposes as tools for understanding and differentiating between sources of resource contributions. This decision is based on an interpretation of Distributed Cognition (Hutchins, 2006) that acknowledges knowledge sources are distributed among people, internal factors, and cultural tools (Brown, 2002).

I contribute to his conception of resources with my inclusion of context-specific resources the teacher design teams drew upon in this study -- collaborative resources. The collaborative resources category described in Figure 6.xx is situation specific, defined by the teacher design teams whose identity was that of teachers whose participation in *EngrTEAMS* is specific to a professional CoP focused on collaborative redesign of integrated STEM curriculum. The combination of the team members' professional identities as teachers, their shared experiences, and goals for creating the integrated STEM curriculum within their cohort defined the context that the resources arose from. Furthermore, unlike the original framework which separated physical resources (curricular) and intellectual (teacher), the category of collaborative resources is a blend of both physical and intellectual resources. Physical resources included the protocol (prompts, role assignments), and assessment documents (written assessments, rubrics). Intellectual resources include facilitation strategies and storytelling. Within the intellectual resources there were subcategories. Facilitation being a subset of protocols, and the types of storytelling (storytelling, co-storytelling, parallel storytelling).

The categories described were not predefined. Rather, they emerged from the teacher design team activities of evaluating student work and collaborative refinement of the STEM curriculum. The identification of these categories did not reveal themselves at a single moment that can be pinpointed. Rather, they emerged from analysis of critical incidents and synthesis of the major assertions of the study. As the complexity of redesigning the STEM curriculum became apparent, it was clear that the teams were drawing upon resources outside of the curricular and teacher resources identified in the literature -- the teacher design teams were drawing upon each other as resources. I refer to the ways in which the teams drew upon each other as resources as collaborative resources. I use collaborative resources as a category in order to distinguish it from teacher and curricular resources, and discern how interactions between the three categories fit within Brown's (2002) scale describing the distribution of resources that inform decisions to offload, adapt or improvise curriculum materials.

Collaborative Resources as a Tool for PDC Development

Applying PDC development within the context of collaborative curriculum redesign has several implications for PDC development, and the use of the DCE framework. First, PDC development -- the ability to identify and mobilize resources to craft instruction (or curriculum) is primarily evidenced by what the teacher design teams discussed and co-designed during the protocol-guided sessions. Modifications to the original curriculum serve as secondary evidence for PDC development, but the absence of modifications does not in-and-of-itself mean the teams' PDC did not evolve. Furthermore, situating the definition of PDC development within curriculum design means PDC development for the teams was not always a one-time event. Rather, sometimes the teams discussed modifications but did not translate them into the final curriculum redesign. This situation resulted in evidence for PDC in terms of *recognizing* available resources for instruction related to the STEM curriculum, but not *mobilizing* the identified resources. In such cases, it does not necessarily mean the teams did not have the capacity to mobilize resources. While that may have been the case, it could also be they simply decided not to make modifications. Thus, PDC development to craft STEM curriculum was not an all-or-none action.

Second, the DCE framework, in its original conception, reflects individual teacher PDC development through interactions of curricular and personal resources. Thus, the offloading, adapting and improvising decisions that resulted from curricular and teacher resource interactions are representations of instruction for themselves -- for their students, their personal goals, beliefs and abilities to craft STEM instruction. The infusion of collaborative resources into the process of instructional design incorporated another level of PDC development into the DCE framework. Whereas initially teacher-curricular interactions reflected classroom-level resources and modifications, the collaborative context transformed classroom-level resources and modifications into a multi-step process of resource interactions and curriculum modification.

When individual teachers brought classroom-level experiences, offloads, adaptations and improvisations to the group, the teacher design teams transformed them into collaborative resources, and used them to make decisions about curriculum redesign. Within the context of the protocol-guided sessions, the individual teachers made the problems they encountered implementing the original curriculum visible to the team, their adapted and improvised solutions to the problems they encountered, and opportunities that arose within the classroom that triggered decisions to modify the co-developed curriculum.

The initial teacher-specific introductions into the protocol sessions reflected individual STEM PDC and curriculum design for their individual classrooms. During the protocol-guided sessions collaborative resources were brought to bear on the individual team member's experiences and curriculum design decisions and informed decisions to offload, adapt or improvise. This process involved several steps consistent with the literature on the various ways teachers engage in curriculum use in their day-to-day practice -- interpretation, selection, reconciliation, accommodation and modification (Brown, 2009). I organize the following section by first discussing the components of collaborative resources, followed by a discussion of how they related to STEM PDC development.

When an individual teacher made their experiences and changes they had made to the co-developed curriculum visible, the teams had to (re)interpret and make decisions about (re)selection of aspects of their original curriculum. If the teacher design teams decided to utilize the new ideas, then they underwent a process of reconciling the new ideas with the original curriculum, accommodating the needs of the other participant teachers, their students, and their teaching contexts with the new ideas. Finally, modifications (offloading, adapting, or improvising) were either made or not made to the final curriculum. These curriculum redesign activities were largely dependent upon collaborative resources of the protocol that established norms and guided the conversation and assessment that focused and maintained focus on student learning. In addition, storytelling and protocol facilitation served as two mediating that mediated how curricular, personal and collaborative resources interacted and used to inform decisions about curriculum modifications.

Contributions to the Literature

Considering curriculum from a design perspective has typically been approached from the classroom level, where an individual teacher's use of curriculum materials is observed and described. However, teachers often work collaboratively with curriculum materials through their school-based CoPs, grade-level teams, and PD programs (as was the case in this study). Therefore, this study's contribution to the literature is both practically and theoretically relevant.

Brown's (2002) contribution to the literature was threefold. First, he developed a scale to describe interactions between teacher and curricular resources that described the distribution of resources in terms of a spectrum. Offloading assigns agency for instruction to the curriculum materials, shared agency for instruction takes place through adapting, and improvising assigns agency primarily to the teacher. Second, he presented the Design Capacity Enactment Framework describes the nature of interactions between resources. Third, he articulated Pedagogical Design Capacity development to describe the factors that define teaching as a design activity, and explain both variation and similarity of curriculum use.

PDC development is premised on teaching as a design activity, and the DCE framework was an attempt to capture the ways teachers exhibit DCE and identify interactions that take place between teachers and curriculum materials. This dissertation explored the ways three teacher design teams co-developed integrated STEM curriculum materials over a yearlong collaboration. The study builds upon Matthew Brown's (2002) work in that, unlike typical curriculum studies, it focuses on the nature of curriculum designs and the factors that influence teacher-curriculum interactions. I built upon his Design Capacity Enactment Framework, introducing a dimension that characterizes the collaborative resources that teacher design teas rely upon for STEM curriculum development. I also introduced the use of protocol interventions as tools to support collaborative teams in growing their understanding of integrated STEM curriculum.

Protocols' Connection to the Teacher-Curriculum Relationship

The use of protocols contributes to the literature in that they provide a way to make teachers' design activity more iterative. Design activity is, by its nature, and iterative process (Moore et al., 2013; Householder & Hailey, 2012). The teacher-curriculum literature characterizes teachers' day-to-day activity as a design process (Brown, 2002, 2009; Brown & Edelson, 2003; Huizinga et al., 2014). The literature also characterizes design activity in terms of five types of teacher-curriculum interactions: interpretation, selection, reconciliation, accommodation, and modification (Brown, 2002, 2009; Remillard, 2005). Furthermore, the teacher design process encompasses producing, revising and the "transformation of curriculum within the ongoing process of classroom activity" (Brown, 2002, p. 84). This study confirmed these findings. The teachers engaged in a wide range of design activity to hone their understanding of STEM curriculum and redesign their curriculum.

This study also provided insights into the role protocols play in making teacher design activity an iterative process. Through post-implementation evaluation and redesign of STEM curriculum the teachers revisited the five types of teacher-curriculum interactions, (re)interpreting the original co-developed curriculum in light of classroom-level events and design activity (offloading, adapting, improvising curriculum), discussing and (re)selecting curricular ideas. In addition, the protocols forced the teacher design teams to reconcile original ideas, accommodate them with classroom-level concerns the teams had for themselves, their students, and teaching context. Thus, protocols overlaid an iterative process of “testing” original curriculum designs in light of insights from the classroom, the original and imagined curriculum, and collaborative resources the teams had available to them. The study also provided insights into the role protocol facilitation played as a collaborative resource the teams drew upon to shift their thinking from the realm of curriculum design for themselves toward curriculum design for other teachers.

Protocols’ Connection to Curriculum Development

Remillard (2005) identified three arenas of mathematics curriculum development: the design arena (selecting materials), the construction arena (enacting curriculum in the classroom) and the mapping arena (determining the overall organization and content of the curriculum). Recall also that McFadden (2015) and McFadden and Roehrig (2017) found that when developing integrated STEM curriculum, teachers tend to remain in the design and construction arena unless nudged into the mapping arena. This study not only confirmed these findings, but identified the *Thinking Through a Task* protocol provides opportunities for nudging the teams into the mapping arena.

The goals for protocol facilitation are generally threefold: establish participant roles during discussion, establish norms for what it discussed, the order in which it is discussed, and the time allotted to each topic. In the case of this study, implementing teacher is responsible for bringing student work, the team is responsible for bringing rubric, and the facilitator's role is to keep the topics of conversation focused on student learning and curriculum. Ideal facilitation strategies are generally to act as timekeeper and redirect when the topic strays. Contributions to the conversation are "allowed," but in a non-directive manner, not introducing new ideas and insights so much as clarifying ideas. In the case of these teams, taking a more directive approach to facilitation was useful during the *Thinking Through a Task* session, because it helped to push the teams out of the *design* and *construction arenas*, into the *curriculum mapping arena* of curriculum development. By pushing back when participants were satisfied to leave the curriculum in its original form, rather than make changes they themselves had either improvised in the classroom or raised as an improvement during the *Looking at Student Work* sessions, the idea of thinking of curriculum for others, rather than solely for themselves, the teams began to see not just that they should think of other teachers, but how to do it.

The Connection of Storytelling to Teacher-Curriculum Interactions

Storytelling, to the best of my knowledge is absent from the literature on PDC development, but this study's findings suggest story affords improvements to the curriculum. Retelling stories from the classroom informs their interpretation, selection, reconciliation, accommodation and modification of STEM curriculum. In this study, the stories were not just about Student X being engaged or classroom management issues. In fact, the vast majority of the stories were "performance moments" (Wortham, 2001) through which the teams recounted problems and designed solutions, and their implications for the curriculum. They used storytelling to share unexpected moments of inspiration and insights, and used the stories as evidence to disagree with components of the curriculum that did not work.

The stories breathed life into the curriculum redesign process, and into STEM PDC development. The stories triggered stories from others that embodied diverse ideas. Through co-storytelling, the team members co-constructed meaning-making related to SEM integration and EDP in a manner that helped them reconcile classroom experiences and their ideas about the co-developed STEM curriculum. Through parallel storytelling, the team members introduced practical and philosophical ideas they perceived as relevant to the redesign of their STEM curriculum. The stories the teams told and retold from classroom-level concerns, informed every level of teacher-curriculum interactions -- interpretation, selection, reconciliation, accommodation and modification. Storytelling served as collaborative resources that interacted with curricular and teacher resources to "change, move, perturb, inform" (Bruner, 1977, p. xv) teacher design teams ability to identify and mobilize resources for STEM curriculum.

Design Implications

This study was situated in Brown's (2009) suggestion for future research into teachers as designers of curriculum materials and Pedagogical Design Capacity to engage the topics of customization of curriculum materials and professional development to support it. The professional development program this study was a part of, *EngrTEAMS*, laid the foundation to build upon his work on PDC with its focus on teacher design teams engaged in STEM curriculum development. The protocol interventions targeted customization of PD in two ways: (i) linking classroom resource use and the decisions to offload, adapt and improvise for curriculum design activity; and (ii) focusing on specific features and affordances of the STEM curriculum, in this case, assessment creation and assessment that promote productive student learning.

The major theoretical contribution to the literature that addresses the call for customization of curriculum and PD, is the understanding the role of context plays in development of STEM PDC, and how it supports curriculum design expertise. Namely, how collaborative resources fit into the Design Enactment Capacity Framework to drive STEM PDC development, and how the use of a variety of facilitation strategies help shift the focus of teachers' design activity from the *design arena* and *construction arena* into the *curriculum mapping arena* of curriculum development. As such, this study build upon the PDC and curriculum design literatures by addressing questions related to the "how" and "why" of STEM PDC development.

There are several implications of this study related to curriculum design and the Design Capacity Enactment Framework, and for professional development that uses protocol interventions to support engaging teacher design teams in curriculum-based reform. First, this study illuminated another dimension to the DCE framework that arises when applied to collaborative teacher design teams -- the role collaborative resources play in developing pedagogical design capacity. The modified Design Capacity Enactment Framework demonstrated how the framework can serve as an analytic tool for groups of teachers working together. Just as the original framework provided an alternative to traditional measures of changes in teacher or student knowledge, that allowed for comparison across teachers and teaching contexts, the Collaborative Design Capacity Enactment Framework can serve as an analytic tool for collaborative work.

Second, the protocol interventions suggest potential benefits of working with groups of teachers during PD opportunities. Protocols may help address gaps in teachers' "design expertise" (Huizinga et al., 2014, p. 33) Huizinga et al. found engaging teachers as curriculum designers brings unique talents and noted gaps. Teachers bring unique knowledge and expertise of students and the classroom to curriculum design. However, teacher design teams rarely employed systematic and productive curriculum evaluation methods to the process of curriculum development. Protocols hold promise as a tool to address the issue of developing design expertise.

Third, leveraging storytelling as a tool for developing teacher design expertise has potential for a wide range of PD activities. Storytelling has been widely applied as an analytic approach in narrative discourse analysis, but to my knowledge, it has not been studied as a tool for developing instructional expertise until this study. Storytelling as a collaborative tool for PDC development was an unanticipated finding of this study, as such, studies that seek to systematically and methodologically investigate it further hold promise for teacher professional learning and development.

Future Research

Future research should continue to explore the use of curriculum materials as a design process, and its relationship to PDC development. This study suggests storytelling and an emphasis on the assessment component, supported with protocols, can be powerful tools for supporting productive use of curriculum materials and for customization of professional development programs. Three suggested avenues for future research relate to: (i) engaging teacher design teams in curriculum testing and redesign; (ii) exploring the relationship between the five types of teacher-curriculum interactions in relation to the DCE framework, and (iii) leveraging storytelling to bridge classroom and curriculum design activity.

Teacher Design Teams and Curriculum Testing and Redesign

One of the enduring challenges of curriculum developers has been to address a host of issues related to what has come to be known as the *intended curriculum* and the *enacted curriculum*. The challenges associated with design curriculum to meet the needs of all students, align with the interests and abilities of all teachers, and address the cultural and linguistic diversity of all instructional contexts is daunting. One way to narrow the gap between the intended and enacted curriculum is to bring teachers in at multiple levels of curriculum design and development.

One possible avenue for developing the teacher design and curriculum development literature further is using what we know to engage teacher design teams in testing and redesigning reform-based curriculum materials. Testing curriculum materials has typically utilized an implement-with-fidelity approach. It may be possible to design the process of testing curriculum materials in ways that bring teachers into the process in fundamentally new ways to benefit both reform efforts and teacher professional learning.

Teacher-Curriculum Interactions and the DCE Framework

This study suggests the relationship between the five types of teacher-curriculum interactions (interpretation, selection, reconciliation, accommodation, modification) have not been adequately explored with regard to the DCE framework and PDC development. Future research that explores PDC development within the various interactions could inform identification and development of the stages of PDC development and corresponding resources teachers draw upon for curriculum use.

Leveraging Storytelling to Bridge Classroom and Curriculum Design Activity

Perhaps the most unexpected finding from this study was the role storytelling played in bridging individual teacher practices with collaborative curriculum design activity. Given the additional fact that storytelling, to my knowledge, has not been explored in relation to teacher design activity of curriculum development activity, storytelling merits exploration in future studies.

This study exists in the space between the curriculum, teacher practice, and STEM reform. As such it encompassed the practical, day-to-day, and theoretical design work of teachers. Future work of interest would shift the perspective of the teacher-curriculum relationship further, while maintaining a research stance that is positioned at the intersection of the classroom and teacher professional learning and development.

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Appendices

Appendix A: Looking at Student Work Protocol

The Looking at Student Work Protocol was adapted from the Standards in Practice (SiP) protocol developed by Education Trust.

Purpose	The purpose of the Examining Student Work Protocol is to share work, gather feedback, and reflect on effectiveness of instruction and/or instructional tools to inform curriculum redesign.
Time	50-60 minutes
Protocol	1. Intro and grounding (2-3 min.): ● Facilitator introduces protocol, guidelines and process. 2. Presenter provides context for assignment (5 min.) ● Share learning goals and standards for assignment ● Share instructions students were given ● Share assessment rubric for assignment 3. Facilitator grounds work and records responses (5 min.) ● Participants identify what students need to know for success. ● Participants identify what students need to be able to do for success. 4. Examination of student work (10 min.) ● Participants look closely at student work without engaging in discussion. ● Participants individually score student work with rubric presenter brought without conversation or clarification about assignment. 5. Discussion (15 min.) ● Participants share scores without discussion about reasons ● Participants discuss overlaps and points of divergence, citing evidence for scores within student work and how it connects to the rubric 6. Feedback and reflection (varies depending on number of people) ● Non-presenting teachers provide feedback. ● Presenter reflects and identifies next steps.

Appendix B: Thinking Through a Task Protocol

An adaptation of the Thinking Through a Lesson Protocol developed by M. Smith, V. Bill, E. Hughes, and colleagues at the Institute for Learning, School of Education, University of Pittsburgh (Blyth et al., 2015, p. 67).

Purpose	The purpose of the Thinking Through a Task Protocol is to develop and refine intellectually challenging tasks that support students' ability to apply mathematics and science to an engineering design challenge.
Time	Varies depending on the group size and facilitator choices for introducing the protocol
Protocol	1. Identify goals: ● What is the task? (What do students do?) ● What content supports the task? (What do they need to know?) ● What are all the ways students will use academic language, skills, and content in completing the task? 2. In-process support ● How will you model use of academic language, skills, and content for students? ● What questions might you ask students as they work on the task? ● What scientific academic language, content, skills will you provide students? 3. Modifications (record on reverse side) ● What modifications did you/will you make to the original design? 4. Assessment ● How will students demonstrate their ability to integrate science, mathematics and engineering design process? ● How will you provide student with feedback on their use of science and mathematics to solve an engineering design challenge? ● How will students use your feedback to revise and improve their design solutions?

C: Interview Questions

Details of Experience

1. Teacher ***describes*** classroom, aka, paint a picture of what a student would experience from the moment he/she enters the room.
(a) Describe Warm-up, Daily Work, Closure, homework sequence.
(b) Classroom rules.
(c) Classroom routines (for whole class, small group, individual, transitions).
(d) Strategies for redirecting behavior.
(e) Consequences for non-conforming, interruptions, inappropriate words/tone (bullying).

2. Teacher describes what she/he does including sequence of lesson segment regularly used in specific class currently being taught including:
(a) Lesson "rules and routines."
(b) Typical planning practices.
(c) How new topic is introduced. (learning objectives, questioning strategies, conceptions.)
(d) Seatwork related to topic.
(e) Discussion of new topic.
(f) Type of homework, assignment of homework and review of homework.
(g) Typical types of formative and summative assessment.
(h) Group work structures, time in groups, purposes/goals of group work related to this lesson.
(i) Views on inquiry activity (5 E's: engage, explore, explain, elaborate, evaluate) and lecture.

2. Teacher ***explains why*** she/he uses each segment, why the goal is important, including contextual factors – this question is repeated until the teacher can't identify another goal. This step reveals higher goals and connections reveal practical reasons for teaching practices:
(a) Classroom rules and routines.
(b) Typical planning practices.
(c) How new topic is introduced. (learning objectives, questioning strategies, conceptions.)
(d) Seatwork related to topic.
(e) Discussion of new topic.
(f) Type of homework, assignment of homework and review of homework.
(g) Typical types of formative and summative assessment.
(h) Group work structures, time in group, purposes/goals of group work related to this lesson.
(i) Views on inquiry activity (5 E's: engage, explore, explain, elaborate, evaluate) and lecture.

3. Ask ***how each segment is prepared*** to find out which design heuristics are currently

used and considered practical reasons that inform a teacher's lesson segment designs in place.
(c) How new topic is introduced. (learning objectives, questioning strategies, conceptions.)
(d) Seatwork related to topic.
(e) Discussion of new topic. How are discussions framed and conducted?
(f) Type of homework, assignment of homework and review of homework. How is homework reviewed? How is feedback provided?
(g) Typical types of formative and summative assessment. How is formative assessment used? How is summative assessment used? How often is each type of formative assessment used?
(h) Group work structures. How much time in groups? What is the purposes/goals of group work related to this lesson? What do transitions look like from whole to small, from whole to individual, from individual to small, or from small to whole?
(i) Views on inquiry activity (5 E's: engage, explore, explain, elaborate, evaluate) and lecture. How often is inquiry used? How often is lecture used? How are textbooks used?

Appendix D: Assertion Table Aligned with Critical Incidents by Protocol

Assessment Rubric Robert Brought to the first Looking at Student Work session. Rubric is from the International Bachelorette (IB) Middle Years Programme (MYP), Year 1, 6th grade physical science

Achievement level	Level descriptor
0	The student does not reach a standard described by any of the descriptors below.
1–2	The student: i. **recognizes some** vocabulary ii. demonstrates **basic** knowledge and understanding of content and concepts through **limited** descriptions and/or examples.
3–4	The student: i. **uses some** vocabulary ii. demonstrates **satisfactory** knowledge and understanding of content and concepts through **simple** descriptions, explanations and/or examples.
5–6	The student: i. **uses considerable relevant** vocabulary, **often accurately** ii. demonstrates **substantial** knowledge and understanding of content and concepts through descriptions, explanations and examples.
7–8	The student: i. **consistently** uses **relevant** vocabulary **accurately** ii. demonstrates **excellent** knowledge and understanding of content and concepts through **detailed** descriptions, explanations and examples.

Appendix E: Assertion Table Aligned with Critical Incidents by Protocol

Team / Protocol	Assertion Number	Assertion	Critical Incidents
DIY: Looking at Student Work	1	The use of a protocol for examining student work makes classroom practice visible.	CI 1: ***KURT:*** *I just realized, we're going through with cost.* CI 3: ***ALEXA:*** *Are we ready to talk about this? . . .*
	2	Facilitation strategies afford collaboration and refinement of curriculum.	CI 2: ***ALEXA:*** *Are we ready to talk about this? . . .*
	3	Making classroom practice visible surfaces problems with the curriculum, solutions to it, and opportunities for improvement.	*CI 3:* ***ALEXA:*** *How about the cost thing? Like, it was impossible to assess cost on these we just did.*
	4	Storytelling mediates development of STEM PDC.	*CI 4:* ***ALEXA:*** *So, how could you connect math?*
	5	Variations in teacher's goals, beliefs and experiences influenced their decisions about curriculum use and redesign.	*CI 5:* ***MATTHEW:*** *To me the most genuine math,*
	6	Customizing the co-developed curriculum through improvisations in the classroom, refines understanding of STEM curriculum.	*CI 6:* ***ALEXA:*** *So, I forgot. I went off my protocol,*
DIY: Thinking Through a Task	7	Facilitation creates opportunities to shift teachers' thinking about curriculum for their classroom towards curriculum for others, and serves as a resources for PDC development.	*CI 7:* ***KATHRYN:*** *That first question, that was the last question I ended up filling out . . .*
	8	The protocol surfaces different goals and values for assessment practices in their own classroom for assessment than they do for the co-developed curriculum.	CI 8: ***KATHRYN****: Well, I just put rubric because that's one thing that I think we both want to change.*
Team PbRE: Looking at Student Work	9	Flexibility in protocol use supports redesign of curriculum specific to assessment.	CI 9: ***ALEXA:*** *You want to do that first [create rubric]*
	10	Coming to understand STEM assessment serves as a collaborative tool that mediates STEM PDC development.	*CI 10:* ***JANICE:*** *So, I think that George and I were starting to get worried that with so much focus on the wind turbine that, that content would be lost*

			CI 11: ***GEORGE:*** *I thought that would make more sense [to design the rubric together*
	11	Combining iterative design of assessment tools with and evaluation of student work, affords adaptations and improvisations to the STEM curriculum.	*CI 12 (2 parts):* ***ALEXA:*** *. . .The other variables, it was pitch, surface area, . . .* ***GEORGE:*** *That's the one thing we would take out though [blade shape variable],*
	12	Improvisations to STEM assessment mediate adaptations to other lessons within the STEM curriculum and inform STEM PDC development.	*CI 13 (2 parts):* ***ALEXA:*** *All right, and the last one is 'we found that the blades produced the most energy when they had 70 degrees of pitch . . .* *Summative Assessment* *CI 14 (2 parts):* ***ALEXA:*** *Let's just give it [scoring student work with the rubric] a try.* *Data Tables from lesson 6*
PbRE: Thinking Through a Task	13	Directive facilitation strategies push the teams to move beyond thinking of curriculum design for their own classroom only, and consider curriculum design for other teachers.	*CI 15:* ***ALEXA:*** *What about, "What are the ways students will use academic language skills and content?"* *CI 16:* ***ALEXA****: How will you provide students with feedback on their use of science and math . . .*
LSS: Looking at Student Work	14	Teachers' beliefs about assessment for student learning constrain collaboration and refinement of the curriculum.	*CI 17:* ***JAYD:*** *The problem is we won't know if they [laser designs] worked but that's okay, because we can't take the time to try them out.*
	15	The *Looking at Student Work* protocol mediates close analysis of student artifacts that supports teachers' ability to learn about student learning.	*CI 18:* ***JAYD:*** *Well, light can be reflected by a mirror, refracted and reflected.* *CI 19:* ***ALEXA:*** *So, next steps?*
	16	Interactions between classroom-level and curriculum level design activity requires creative facilitation strategies.	*CI 20:* ***ALEXA:*** *Okay, I had a plan for today that included the writing piece.*
LSS: Thinking Through a Task	17	Teachers draw upon their personal resources to address perceived weaknesses in the curriculum and share solutions through storytelling.	*CI 21:* ***JAYD:*** *(talking to Mark) I like when you had them go around and hit targets.*
	18	Parallel storytelling serves as a mediating tool for understanding student learning and STEM curriculum.	*CI 22:* ***ALEXA:*** *So let's talk about those modifications* *CI 23:* ***ROBERT:*** *I mean, you can tell that they're learning.*

Appendix F: Assertion Table Aligned with Research Questions

Team / Protocol	Assertion Number	Assertion	Research Question
DIY: Looking at Student Work	1	The use of a protocol for examining student work makes classroom practice visible.	*2. How does the use of a protocol for examination of student work afford and constrain collaboration and redesign of co-developed curriculum?*
	2	Facilitation strategies afford collaboration and refinement of curriculum.	*2. How does the use of a protocol for examination of student work afford and constrain collaboration and redesign of co-developed curriculum?*
	3	Making classroom practice visible surfaces problems with the curriculum, solutions to it, and opportunities for improvement.	*1. How does STEM PDC develop and evolve in teacher design teams while examining student work and redesigning a co-developed STEM curriculum?*
	4	Storytelling mediates development of STEM PDC.	*1. How does STEM PDC develop and evolve in teacher design teams while examining student work and redesigning a co-developed STEM curriculum?*
	5	Variations in teacher's goals, beliefs and experiences influenced their decisions about curriculum use and redesign.	*1. How does STEM PDC develop and evolve in teacher design teams while examining student work and redesigning a co-developed STEM curriculum?*
	6	Customizing the co-developed curriculum through improvisations in the classroom, refines understanding of STEM curriculum.	*1. How does STEM PDC develop and evolve in teacher design teams while examining student work and redesigning a co-developed STEM curriculum?*
DIY: Thinking Through a Task	7	Facilitation creates opportunities to shift teachers' thinking about curriculum for their classroom towards curriculum for others, and serves as a resources for PDC development.	*1. How does STEM PDC develop and evolve in teacher design teams while examining student work and redesigning a co-developed STEM curriculum?* *2. How does the use of a protocol for examination of student work afford and constrain collaboration and redesign of co-developed curriculum?* *3. How does the use of a protocol for designing curriculum materials afford and constrain collaboration and redesign of co-developed curriculum?*
	8	The protocol surfaces different goals and values for assessment practices in their own classroom for assessment than they do for the co-developed curriculum.	*3. How does the use of a protocol for designing curriculum materials afford and constrain collaboration and redesign of co-developed curriculum?*
Team PbRE: Looking at Student Work	9	Flexibility in protocol use supports redesign of curriculum specific to assessment.	*3. How does the use of a protocol for designing curriculum materials afford and constrain collaboration and redesign of co-developed curriculum?*

	10	Coming to understand STEM assessment serves as a collaborative tool that mediates STEM PDC development.	*1. How does STEM PDC develop and evolve in teacher design teams while examining student work and redesigning a co-developed STEM curriculum?* *3. How does the use of a protocol for designing curriculum materials afford and constrain collaboration and redesign of co-developed curriculum?*
	11	Combining iterative design of assessment tools with and evaluation of student work, affords adaptations and improvisations to the STEM curriculum.	*2. How does the use of a protocol for examination of student work afford and constrain collaboration and redesign of co-developed curriculum?* *3. How does the use of a protocol for designing curriculum materials afford and constrain collaboration and redesign of co-developed curriculum?*
	12	Improvisations to STEM assessment mediate adaptations to other lessons within the STEM curriculum and inform STEM PDC development.	*1. How does STEM PDC develop and evolve in teacher design teams while examining student work and redesigning a co-developed STEM curriculum?* *2. How does the use of a protocol for examination of student work afford and constrain collaboration and redesign of co-developed curriculum?* *3. How does the use of a protocol for designing curriculum materials afford and constrain collaboration and redesign of co-developed curriculum?*
PbRE: Thinking Through a Task	13	Directive facilitation strategies push the teams to move beyond thinking of curriculum design for their own classroom, and consider curriculum design for other teachers.	*1. How does STEM PDC develop and evolve in teacher design teams while examining student work and redesigning a co-developed STEM curriculum?* *2. How does the use of a protocol for examination of student work afford and constrain collaboration and redesign of co-developed curriculum?* *3. How does the use of a protocol for designing curriculum materials afford and constrain collaboration and redesign of co-developed curriculum?*
LSS: Looking at Student Work	14	Teachers' beliefs about assessment for student learning constrain collaboration and refinement of the curriculum.	*2. How does the use of a protocol for examination of student work afford and constrain collaboration and redesign of co-developed curriculum?*
	15	The *Looking at Student Work* protocol affords close analysis of student artifacts that supports teachers' ability to understand student learning.	*2. How does the use of a protocol for examination of student work afford and constrain collaboration and redesign of co-developed curriculum?*

	16	Interactions between classroom-level and curriculum level design activity requires creative facilitation strategies.	*1. How does STEM PDC develop and evolve in teacher design teams while examining student work and redesigning a co-developed STEM curriculum?*
LSS: Thinking Through a Task	17	Teachers draw on personal resources to address problems with the curriculum during implementation, and share solutions with teacher design teams through storytelling.	*1. How does STEM PDC develop and evolve in teacher design teams while examining student work and redesigning a co-developed STEM curriculum?*
	18	Parallel storytelling serves as a mediating tool to deepen understanding of student learning and STEM curriculum.	*1. How does STEM PDC develop and evolve in teacher design teams while examining student work and redesigning a co-developed STEM curriculum?*